NIST NCSTAR 1A

Federal Building and Fire Safety Investigation of the World Trade Center Disaster

Final Report on the Collapse of World Trade Center Building 7

Draft for Public Comment

National Institute of Standards and Technology
U.S. Department of Commerce

NIST NCSTAR 1A

Federal Building and Fire Safety Investigation of the World Trade Center Disaster

Final Report on the Collapse of World Trade Center Building 7

August, 2008

U.S. Department of Commerce
Carlos M. Gutierrez, Secretary

National Institute of Standards and Technology
James Turner, Deputy Director

Disclaimer No. 1

Certain commercial entities, equipment, products, or materials are identified in this document in order to describe a procedure or concept adequately or to trace the history of the procedures and practices used. Such identification is not intended to imply recommendation, endorsement, or implication that the entities, products, materials, or equipment are necessarily the best available for the purpose. Nor does such identification imply a finding of fault or negligence by the National Institute of Standards and Technology.

Disclaimer No. 2

The policy of NIST is to use the International System of Units (metric units) in all publications. In this document, however, units are presented in metric units or the inch-pound system, whichever is prevalent in the discipline.

Disclaimer No. 3

Pursuant to section 7 of the National Construction Safety Team Act, the NIST Director has determined that certain evidence received by NIST in the course of this Investigation is “voluntarily provided safety-related information” that is “not directly related to the building failure being investigated” and that “disclosure of that information would inhibit the voluntary provision of that type of information” (15 USC 7306c).

In addition, a substantial portion of the evidence collected by NIST in the course of the Investigation has been provided to NIST under nondisclosure agreements.

Disclaimer No. 4

NIST takes no position as to whether the design or construction of a WTC building was compliant with any code since, due to the destruction of the WTC buildings, NIST could not verify the actual (or as-built) construction, the properties and condition of the materials used, or changes to the original construction made over the life of the buildings. In addition, NIST could not verify the interpretations of codes used by applicable authorities in determining compliance when implementing building codes. Where an Investigation report states whether a system was designed or installed as required by a code *provision*, NIST has documentary or anecdotal evidence indicating whether the requirement was met, or NIST has independently conducted tests or analyses indicating whether the requirement was met.

Use in Legal Proceedings

No part of any report resulting from a NIST investigation into a structural failure or from an investigation under the National Construction Safety Team Act may be used in any suit or action for damages arising out of any matter mentioned in such report (15 USC 281a; as amended by P.L. 107-231).

National Institute of Standards and Technology National Construction Safety Team Act Report 1A
Natl. Inst. Stand. Technol. Natl. Constr. Sfty. Tm. Act Rpt. 1A, 116 pages (August 2008)
CODEN: NSPUE2

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 2005

For sale by the Superintendent of Documents, U.S. Government Printing Office
Internet: bookstore.gpo.gov — Phone: (202) 512-1800 — Fax: (202) 512-2250
Mail: Stop SSOP, Washington, DC 20402-0001

NATIONAL CONSTRUCTION SAFETY TEAM FOR THE FEDERAL BUILDING AND FIRE SAFETY INVESTIGATION OF THE WORLD TRADE CENTER DISASTER

S. Shyam Sunder, Sc.D. (NIST)	Lead Investigator
Richard G. Gann, Ph.D. (NIST)	Final Report Editor; Project Leader, Project 5: Reconstruction of Thermal and Tenability Environment
William L. Grosshandler, Ph.D. (NIST)	Associate Lead Investigator; Project Leader, Project 4: Investigation of Active Fire Protection Systems
H.S. Lew, Ph.D., P.E. (NIST)	Co-Project Leader, Project 1: Analysis of Building and Fire Codes and Practices
Richard W. Bukowski, P.E. (NIST)	Co-Project Leader, Project 1: Analysis of Building and Fire Codes and Practices
Fahim Sadek, Ph.D. (NIST)	Project Leader, Project 2: Baseline Structural Performance and Aircraft Impact Damage Analysis
Frank W. Gayle, Ph.D. (NIST)	Project Leader, Project 3: Mechanical and Metallurgical Analysis of Structural Steel
John L. Gross, Ph.D., P.E. (NIST)	Co-Project Leader, Project 6: Structural Fire Response and Collapse Analysis
Therese P. McAllister, Ph.D., P.E. (NIST)	Co-Project Leader, Project 6: Structural Fire Response and Collapse Analysis
Jason D. Averill (NIST)	Project Leader, Project 7: Occupant Behavior, Egress, and Emergency Communications
J. Randall Lawson (NIST)	Project Leader, Project 8: Fire Service Technologies and Guidelines
Harold E. Nelson, P.E.	Fire Protection Engineering Expert
Stephen A. Cauffman (NIST)	Program Manager

This page intentionally left blank.

CONTRIBUTORS TO THE INVESTIGATION OF WTC 7

NIST TECHNICAL STAFF

Mohsen Altafi
Elisa Baker
Stephen Banovic
Carlos Beauchamp
Dale Bentz
Charles Bouldin
Paul Brand
Lori Brassell
Kathy Butler
Nicholas Carino
Sandy Clagett
Ishmael Conteh
Matthew Covin
Frank Davis
David Dayan
Laurean DeLauter
Stuart Dols
Michelle Donnelly
Dat Duthinh
David Evans
Richard Fields
James Filliben
Tim Foecke
Glenn Forney
William Fritz
Dave Kelley
Mark Kile
William Luecke
Joseph Mains
David McColskey
Chris McCowan
Jay McElroy
Kevin McGrattan
Lakeshia Murray
Joshua Novosel
Victor Ontiveros
Richard Peacock
Max Peltz
Lisa Petersen
Long Phan
William Pitts
Rochelle Plummer
Kuldeep Prasad
Natalia Ramirez
Paul Reneke
Lonn Rodine
Schuyler Ruitberg
Jose Sanchez
Raymond Santoyo
Steven Sekellick
Thomas Siewert
Emil Simiu
Laura Sugden
Robert Vettori
John Widmann
Brendan Williams
Maureen Williams
Robert Zarr

NIST EXPERTS AND CONSULTANTS

Najib Abboud
William Baker
Gene Corley
Vincent Dunn
Jim Harris
Steven Hill
John Hodgens
Valentine Junker
Kevin Malley
Shankar Nair

DEPARTMENT OF COMMERCE AND NIST INSTITUTIONAL SUPPORT

Tomara Arrington
Kellie Beall
Tara Brown
Craig Burkhardt
Deborah Cramer
Gail Crum
Jane Dana
Matthew Heyman
James Hill
Nuala O'Connor Kelly
Fred Kopatich
Kenneth Lechter

Melissa Lieberman
Darren Lowe
Romena Moy
Michael E. Newman
Gail Porter
Karen Perry
Sharon Rinehart
Michael Rubin
John Sanderson
Joan Smith
Jack Snell
Nancy Snyder
Kelly Talbott
Michael R. Rubin

NIST Contractors

Applied Research Associates, Inc.

Steven Kirkpatrick
Robert A. MacNeill
Brian D. Peterson
Robert T. Bocchieri

Gilsanz Murray Steficek, LLP

Ramon Gilsanz

Independent Contractors

William Koffel
William Thornton
Mark Loizeaux

HeiTech Services, Inc.

Sonya D. Wilson

Rolf Jensen & Associates, Inc.

Ray Grill
Ed Armm
Tom Brown
Duane Johnson
Bob Keough
Joseph Razz

Simpson Gumpertz & Heger Inc

Mehdi Zarghamee
Ömer O. Erbay
Andrew T. Sarawit

U.S. Securities and Exchange Commission

Al Basile
Robert DeLeonardus
Ray Ferrari
Richard Lee

Siemens

Steven Shamash
John Farrington
Robert Salamone

Silverstein Properties

Larry Silverstein
Kent Anker
Dara McQuillan
Steven Nathan
Walter Weems

Simpson, Thacher & Bartlett LLP

Jamie Gamble

Wachtel, Lipton, Rosen & Katz

Mark Wolinsky
Ian Botchko
Andrew Cheun
Gina Iannello

COOPERATING ORGANIZATIONS

American Express

Peter Kane
Carol Schwartz

AP

Mike LeTourneau

Bernstein Associates Photographers

Neal Lehrer

CNN

David Sheehan
Felicia Dunston

Citigroup, Inc.

James Goddard

Cleary Gottlieb Steen & Hamilton LLP

Karen Bekker
Adam Itzkowitz
Thomas Moloney
Christopher Moore
Rahul Mukhi
Kimberly Spiering
John VanSickle

<u>Clifford Law Offices</u>
Timothy S. Tomasik

<u>Con Edison</u>
Martin Heslin

<u>Fire Department of the City of New York</u>
Amy Adelman
Alexandra Fischer
John Tsanas

<u>Flack & Kurtz</u>

<u>Flemming, Zulack, Williamson, Zauderer, LLP</u>
Gregg Kanter

<u>Fox News</u>
Christopher J. Silvestri

<u>Friedman Kaplan Seiler and Adelman</u>
Kent Anker

<u>G&S Technologies</u>
Jay Spector

<u>General Services Administration</u>
Mary Guida

<u>Gogick, Byrne & O'Neill, LLP</u>
Stephen P. Schreckinger
Kevin J. O'Neill

<u>GSA</u>
Maria Guida

<u>Keegan Werlin LLP</u>
Richard B. Kirby
Ryan T. Parsons (paralegal)

Lower Manhattan Development Corporation

David Ridley
Irene Chang

National Commission on Terrorist Attacks upon the United States

Madeline Blot
Sam M. W. Casperson
George L. Delgrosso
Daniel Marcus
James Miller
Catherine S. Taylor

New York City Department of Design and Construction (DDC)

David J. Varoli

New York City Law Department

Lawrence S. Kahn
Ken Becker
Faye Lubinof
Jay L. Cohen
Gary Shaffer
Katherine Winningham
Jessie Levine

New York City Police Department

Michael F. Healey

New York City Transit Authority

Veronica Hakim
Paul Fleuranges
Kavita Bhatt

The Hartford Insurance Co.

Mary Chepovsky

The Port Authority of New York and New Jersey

James Begley
Saroj Bhol
Jeffrey Gertier
Frank Lombardi
Alan Reiss
Timothy Stickelman

Robbins Kaplan Miller & Ciresi

Margo Brownell

Schiff Harden

Beth Jacob

Siemens Corporation

Steven R. Shamash
Bob Salamone

SOM
Jeffrey Goldsmith
Sharyn Fitter

Testwell Craig
Richard Bridglal

Turner Construction Company
Bernadette Forte

UHY Advisors FLVS, Inc.
Jonathan L. Newcomb

U.S. Securities and Exchange Commission
Richard D. Lee
Robert DeLeonardis

Weidlinger Associates Inc.
Najib N. Abboud

W.R. Grace
Mark A. Shmorhun
Robert J. Bettacchi
Michael B. Cohan

Zetlin & DeChiara
David Abramovitz

DEDICATION

On the morning of September 11, 2001, Americans and people around the world were shocked by the destruction of the World Trade Center (WTC) in New York City and the devastation of the Pentagon near Washington, D.C., after large aircraft were flown into the buildings, and the crash of an aircraft in a Pennsylvania field that averted further tragedy. Seven years later, the world has been changed irrevocably by those terrorist attacks. For some, the absence of people close to them is a constant reminder of the unpredictability of life and death. For millions of others, the continuing threats of further terrorist attacks affect how we go about our daily lives and the attention we must give to homeland security and emergency preparedness.

Within the construction, building, and public safety communities, there arose a question pressing to be answered: How can we reduce our vulnerability to such attacks, and how can we increase our preparedness and safety while still ensuring the functionality of the places in which we work and live?

This Investigation has, to the best extent possible, reconstructed the response of the WTC towers, WTC 7, and the people on site to the consequences of the aircraft impacts. It provides improved understanding to the professional communities and building occupants whose action is needed and to those most deeply affected by the events of that day. In this spirit, this report is dedicated to those lost in the disaster, to those who have borne the burden to date, and to those who will carry it forward to improve the safety of buildings.

This page intentionally left blank.

ABSTRACT

This is the final report on the National Institute of Standards and Technology (NIST) investigation of the collapse of World Trade Center Building 7 (WTC 7), conducted under the National Construction Safety Team Act. This report describes how the fires that followed the impact of debris from the collapse of WTC 1 (the north tower) led to the collapse of WTC 7; an evaluation of the building evacuation and emergency response procedures; what procedures and practices were used in the design, construction, operation, and maintenance of the building; and areas in current building and fire codes, standards, and practices that warrant revision. Extensive details are found in the companion reports, NIST NCSTAR 1-9 and NIST NCSTAR 1-9A.

Also in this report is a summary of how NIST reached its conclusions. NIST complemented in-house expertise with private sector technical experts; accumulated copious documents, photographs, and videos of the disaster; conducted first-person interviews of building occupants and emergency responders; analyzed the evacuation and emergency response operations in and around WTC 7; performed computer simulations of the behavior of WTC 7 on September 11, 2001; and combined the knowledge gained into a probable collapse sequence.

The report concludes with a list of 13 recommendations for action in the areas of increased structural integrity, enhanced fire endurance of structures, new methods for fire resistant design of structures, enhanced active fire protection, improved emergency response, improved procedures and practices, and education and training. One of these is new; the other 12 are reiterated from the investigation into the collapse of the WTC towers. Each of the 13 is relevant to WTC 7.

Keywords: building evacuation, emergency response, fire safety, structural collapse, tall buildings, World Trade Center.

This page intentionally left blank.

TABLE OF CONTENTS

National Construction Safety Team for the Federal Building and Fire Safety Investigation of the World Trade Center Disaster iii

Contributors to the Investigation of WTC 7 v

Dedication xi

Abstract xiii

List of Figures xix

List of Tables xxi

List of Acronyms and Abbreviations xxiii

Preface xxv

Executive Summary xxxi

Chapter 1 **The New York City World Trade Center Building 7 .... 1**

1.1 The World Trade Center Complex 1

1.2 WTC 7 1

1.2.1 The Edifice 1

1.2.2 The Con Edison Substation 3

1.2.3 The Structure 5

1.2.4 Fire Protection 7

1.2.5 The Workplace 8

1.2.6 The Combustible Contents 9

Chapter 2 **The Account of WTC 7 .... 13**

2.1 Introduction 13

2.2 Activity at the WTC 7 Site 13

2.2.1 8:46 a.m. to 9:59 a.m. EDT 13

2.2.2 9:59 a.m. to 10:28 a.m. EDT 14

2.2.3 10:29 a.m. to 5:21 p.m. EDT 16

2.3 Progress of the Fires in WTC 7 16

2.4 The Probable Collapse Sequence 19

Chapter 3 **Deriving The Probable Collapse Sequence 21**

3.1 Gathering of Evidence 21

3.2 The Leading Hypothesis 21

3.3 Hypothetical Blast Scenarios 22
3.4 The Four-step Simulation Process 24
3.4.1 Technical Approach 24
3.4.2 Fires Simulated 25
3.4.3 Fire Dynamics Simulator (FDS) 28
3.4.4 Fire Structure Interface (FSI) 28
3.4.5 Structural Analysis of the Initial Failure Event using ANSYS 32
3.4.6 Global Collapse Analysis using LS-DYNA 34
3.5 Accuracy of the Probable Collapse Sequence 38
3.5.1 Aspects prior to the Global Collapse 38
3.5.2 Aspects following the Collapse Initiation 40
3.5.3 Accuracy Appraisal 40
3.6 Collapse Time 40

Chapter 4 **Principal Findings 43**
4.1 Introduction 43
4.2 Summary 43
4.3 The Mechanisms of Building Collapse 46
4.3.1 Debris Impact Damage from the Collapse of WTC 1 46
4.3.2 Reconstruction of the Fires 46
4.3.3 Fire-induced Thermal Effects 48
4.3.4 Structural Response and Collapse 49
4.4 Life Safety Factors 51
4.4.1 Evacuation of WTC 7 51
4.4.2 Emergency Response 52
4.5 Codes, Standards, and Practices 52
4.5.1 General 52
4.5.2 Building Design and Structural Safety 53
4.5.3 SFRM Requirements and Application 54
4.5.4 Fire Safety and Fire Protection Systems 54
4.6 Future Factors That Could Have Mitigated Structural Collapse 55
4.7 Human Performance Factors 55

Chapter 5 **Recommendations 57**
5.1 General 57

NIST's Recommendations for Improving the Safety of Buildings, Occupants, and Emergency Responders 58
5.1.1 Group 1. Increased Structural Integrity 58
5.1.2 Group 2. Enhanced Fire Endurance of Structures 58
5.1.3 Group 3. New Methods for Fire Resistant Design of Structures 61
5.1.4 Group 4. Improved Active Fire Protection 63
5.1.5 Group 6. Improved Emergency Response 63
5.1.6 Group 7. Improved Procedures and Practices 64
5.1.7 Group 8. Education and Training 65

National Construction Safety Team Act 67

World Trade Center Investigation Publications 73

This page intentionally left blank.

LIST OF FIGURES

Figure P–1. Technical components of the Federal Building and Fire Safety Investigation of the WTC Disaster. xxvii

Figure 1–1. The World Trade Center in Lower Manhattan. 2

Figure 1–2. Photograph of the World Trade Center Complex, showing WTC 7. 3

Figure 1–3. Footprints of the Con Edison substation and WTC 7. 4

Figure 1–4. Aerial view from the north side of WTC 7, showing the Con Edison substation........ 4

(Photo taken prior to September 11, 2001.) 4

Figure 1–5. Typical WTC 7 floor showing locations of the columns, girders, and beams. 6

Figure 1–6. 3D schematic view of transfer trusses and girders between Floors 5 and 7. 6

Figure 1–7. Schematic drawing of the elevators in WTC 7. 8

Figure 1–8. Schematic of Floor 8........ 10

Figure 1–9. Schematic of Floor 11........ 10

Figure 1–10. Section view of fuel oil distribution components in WTC 7. 12

Figure 2–1. Observed damage to WTC 7 following the collapse of WTC 1. 15

Figure 2–2. Eastward buckling of Column 79, viewed from the southeast. 20

Figure 3–1. Peak overpressure and broken window locations. 23

Top: 9 lb shaped charge; bottom: 2 lb charge. 23

Figure 3–2. WTC 7 analysis sequence and interdependencies. 24

Figure 3–3. Layout of the 6th floor of WTC 7. 27

Figure 3–4. Schematic of the 5th floor of WTC 7 showing the locations of the emergency power system components. 27

Figure 3–5. Progression of simulated fire on Floor 8 of WTC 7. 29

Figure 3–6. Progression of simulated fire on Floor 12 of WTC 7. 30

Figure 3–7. View from the northeast of the computed heating of the lower 16 floors of WTC 7 at five different instants in time. 31

Figure 3–8. Computed temperature distribution (ºC) in the top layer of the concrete slab of Floor 12 at five different instants in time. 31

Figure 3–9. Damage state of connections in Floor 13 for Case B temperatures. 33

Figure 3–10. Vertical progression of failures on the east side of the building at 0.5 s following the initiation of the collapse. 36

Figure 3–11. Failure of Columns 77 and 78 due to failure of Truss 2 fails from debris impact at 2.5 s following the initiation of the collapse. 36

Figure 3–12. Failure of Columns 73 to 75 from the load redistribution and debris impact at 4.5 s following the initiation of the collapse. 37

Figure 3–13. Buckling of all interior columns at 6.5 s following the initiation of the collapse.................. 37
Figure 3-14. Buckling of the lower exterior columns within 1 s of Figure 3–13....................................... 38

LIST OF TABLES

Table P–1. Federal Building and Fire Safety Investigation of the WTC Disaster. xxvi
Table P–2. Public meetings and briefings of the WTC Investigation. xxix
Table 1–1. Use of floors in WTC 7 9
Table 1–2. Emergency power systems in WTC 7. 11
Table 3–1. Comparison of global structural model predictions and observations for WTC 7, Case B. 39

This page intentionally left blank.

List of Acronyms and Abbreviations

Acronyms

ASCE	American Society of Civil Engineers
ASTM	ASTM International
BPS	Building Performance Study
FCD	Fire Command Desk
FDNY	The Fire Department of the City of New York
FDS	Fire Dynamics Simulator
FEMA	Federal Emergency Management Agency
FSI	Fire Structure Interface
IBC	International Building Code
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NYC	New York City
NYCBC	New York City Building Code
NYPD	New York City Police Department
NYS	New York State
OEM	New York Mayor's Office of Emergency Management
PANYNJ	The Port Authority of New York and New Jersey
PAPD	Port Authority Police Department
SFRM	sprayed fire-resistive material
SSB	Solomon Smith Barney
UL	Underwriters Laboratories
USC	United States Code
USFA	United States Fire Administration
WTC	World Trade Center
WTC 1	World Trade Center 1 (North Tower)
WTC 2	World Trade Center 2 (South Tower)
WTC 7	World Trade Center 7

Abbreviations and Conversion Factors

dB	decibel	
°C	degree Celsius	T (ºC) = 5/9 [T (ºF) – 32]
°F	degree Fahrenheit	
ft	feet	
gal	gallon	1 gal = 3.78 x 10^{-3} m^3
in.	inch	
kg	kilogram	
kip	1,000 lb	
ksi	1,000 lb/$in.^2$	
lb	pound	1 lb = 0.453 kg
m	meter	1 m = 3.28 ft
μm	micrometer	
min	minute	
MJ	megajoule	
MW	megawatt	
psi	pounds per square inch	
s	second	
T	temperature	

PREFACE

Genesis of This Investigation

Immediately following the terrorist attack on the World Trade Center (WTC) on September 11, 2001, the Federal Emergency Management Agency (FEMA) and the American Society of Civil Engineers began planning a building performance study of the disaster. The week of October 7, as soon as the rescue and search efforts ceased, the Building Performance Study Team went to the site and began its assessment. This was to be a brief effort, as the study team consisted of experts who largely volunteered their time away from their other professional commitments. The Building Performance Study Team issued its report in May 2002, fulfilling its goal "to determine probable failure mechanisms and to identify areas of future investigation that could lead to practical measures for improving the damage resistance of buildings against such unforeseen events."

On August 21, 2002, with funding from the U.S. Congress through FEMA, the National Institute of Standards and Technology (NIST) announced its building and fire safety investigation of the WTC disaster. On October 1, 2002, the National Construction Safety Team Act (Public Law 107-231), was signed into law. (A copy of the Public Law is included in Appendix A). The NIST WTC Investigation was conducted under the authority of the National Construction Safety Team Act.

The goals of the investigation of the WTC disaster were:

- To investigate the building construction, the materials used, and the technical conditions that contributed to the outcome of the WTC disaster.
- To serve as the basis for:
  - Improvements in the way buildings are designed, constructed, maintained, and used;
  - Improved tools and guidance for industry and safety officials;
  - Recommended revisions to current codes, standards, and practices; and
  - Improved public safety.

The specific objectives were:

1. Determine why and how WTC 1 and WTC 2 collapsed following the initial impacts of the aircraft and why and how WTC 7 collapsed;
2. Determine why the injuries and fatalities were so high or low depending on location, including all technical aspects of fire protection, occupant behavior, evacuation, and emergency response;
3. Determine what procedures and practices were used in the design, construction, operation, and maintenance of WTC 1, 2, and 7; and
4. Identify, as specifically as possible, areas in current building and fire codes, standards, and practices that warrant revision.

NIST is a nonregulatory agency of the U.S. Department of Commerce. The purpose of NIST investigations is to improve the safety and structural integrity of buildings in the United States, and the focus is on fact finding. NIST investigative teams are authorized to assess building performance and emergency response and evacuation procedures in the wake of any building failure that has resulted in substantial loss of life or that posed significant potential of substantial loss of life. NIST does not have the statutory authority to make findings of fault nor negligence by individuals or organizations. Further, no part of any report resulting from a NIST investigation into a building failure or from an investigation under the National Construction Safety Team Act may be used in any suit or action for damages arising out of any matter mentioned in such report (15 USC 281a, as amended by Public Law 107-231).

Organization of the Investigation

The National Construction Safety Team for this Investigation, appointed by the then NIST Director, Dr. Arden L. Bement, Jr., was led by Dr. S. Shyam Sunder. Dr. William L. Grosshandler served as Associate Lead Investigator, Mr. Stephen A. Cauffman served as Program Manager for Administration, and Mr. Harold E. Nelson served on the team as a private sector expert. The Investigation included eight interdependent projects whose leaders comprised the remainder of the team. A detailed description of each of these eight projects is available at http://wtc.nist.gov. The purpose of each project is summarized in Table P–1, and the key technical components are illustrated in Fig. P–1.

Table P–1. Federal Building and Fire Safety Investigation of the WTC Disaster.

Technical Area and Project Leader	Project Purpose
Analysis of Building and Fire Codes and Practices; Project Leaders: Dr. H. S. Lew and Mr. Richard W. Bukowski	Document and analyze the code provisions, procedures, and practices used in the design, construction, operation, and maintenance of the structural, passive fire protection, and emergency access and evacuation systems of WTC 1, 2, and 7.
Baseline Structural Performance and Aircraft Impact Damage Analysis; Project Leader: Dr. Fahim H. Sadek	Analyze the baseline performance of WTC 1 and WTC 2 under design, service, and abnormal loads, and aircraft impact damage on the structural, fire protection, and egress systems.
Mechanical and Metallurgical Analysis of Structural Steel; Project Leader: Dr. Frank W. Gayle	Determine and analyze the mechanical and metallurgical properties and quality of steel, weldments, and connections from steel recovered from WTC 1, 2, and 7.
Investigation of Active Fire Protection Systems; Project Leader: Dr. David D. Evans; Dr. William Grosshandler	Investigate the performance of the active fire protection systems in WTC 1, 2, and 7 and their role in fire control, emergency response, and fate of occupants and responders.
Reconstruction of Thermal and Tenability Environment; Project Leader: Dr. Richard G. Gann	Reconstruct the time-evolving temperature, thermal environment, and smoke movement in WTC 1, 2, and 7 for use in evaluating the structural performance of the buildings and behavior and fate of occupants and responders.
Structural Fire Response and Collapse Analysis; Project Leaders: Dr. John L. Gross and Dr. Therese P. McAllister	Analyze the response of the WTC towers to fires with and without aircraft damage, the response of WTC 7 in fires, the performance of composite steel-trussed floor systems, and determine the most probable structural collapse sequence for WTC 1, 2, and 7.
Occupant Behavior, Egress, and Emergency Communications; Project Leader: Mr. Jason D. Averill	Analyze the behavior and fate of occupants and responders, both those who survived and those who did not, and the performance of the evacuation system.
Emergency Response Technologies and Guidelines; Project Leader: Mr. J. Randall Lawson	Document the activities of the emergency responders from the time of the terrorist attacks on WTC 1 and WTC 2 until the collapse of WTC 7, including practices followed and technologies used.

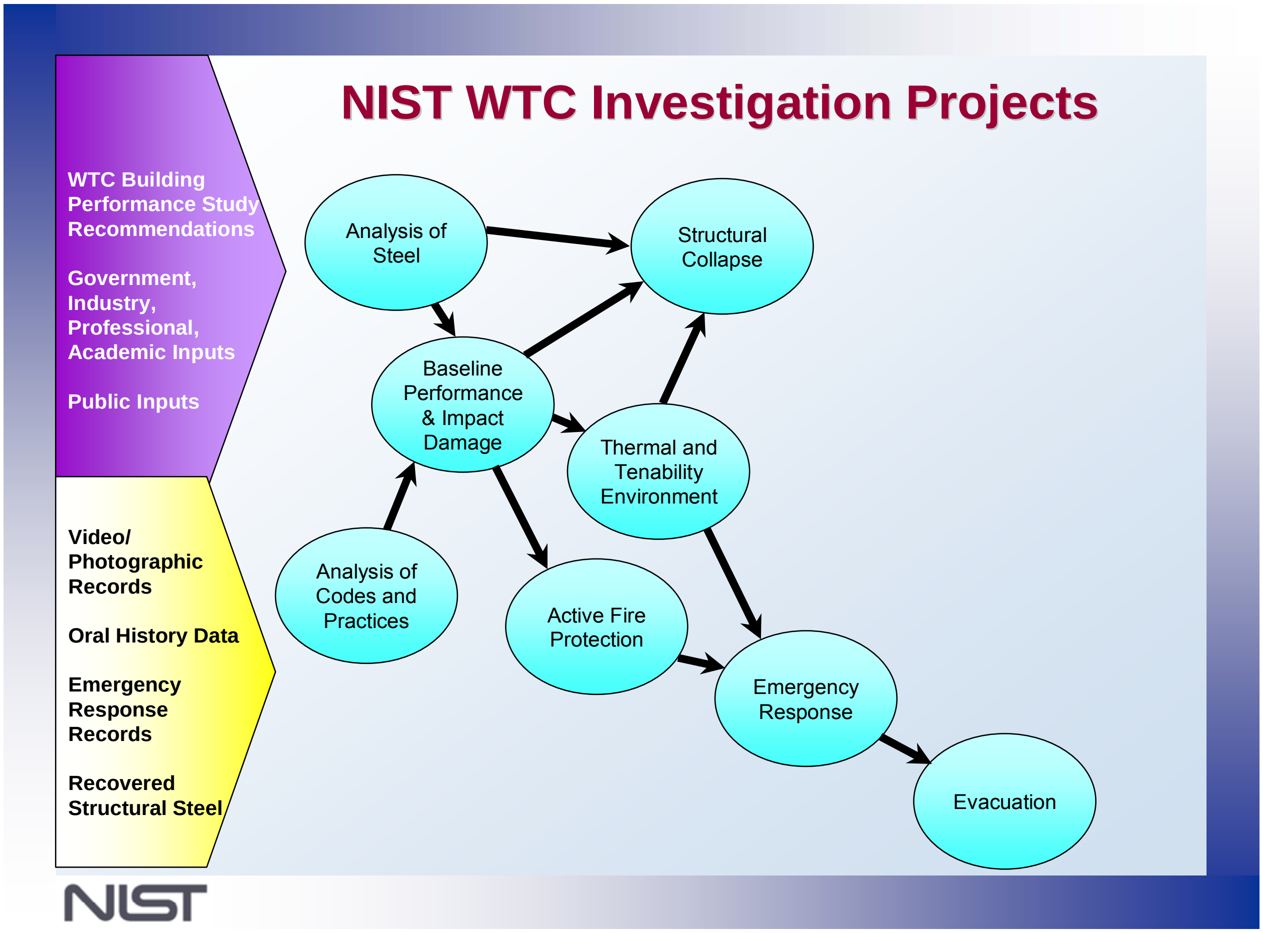


Figure P–1. Technical components of the Federal Building and Fire Safety Investigation of the WTC Disaster.

National Construction Safety Team Advisory Committee

The NIST Director also established an advisory committee as mandated under the National Construction Safety Team Act. The initial members of the committee were appointed following a public solicitation. These were, with their terms in parentheses:

- Paul Fitzgerald, Executive Vice President (retired) FM Global, National Construction Safety Team Advisory Committee Chair (2003-2009)
- John Barsom, President, Barsom Consulting, Ltd. (2003-2011).
- John Bryan, Professor Emeritus, University of Maryland (2003-2004)
- David Collins, President, The Preview Group, Inc. (2003-2010)
- Glenn Corbett, Professor, John Jay College of Criminal Justice (2003-2006)
- Philip DiNenno, President, Hughes Associates, Inc.(2003-2006)

- Robert Hanson, Professor Emeritus, University of Michigan (2003-2009)
- Charles Thornton, Co-Chairman and Managing Principal, The Thornton-Tomasetti Group, Inc. (2003-2011)
- Kathleen Tierney, Director, Natural Hazards Research and Applications Information Center, University of Colorado at Boulder (2003-2007)
- Forman Williams, Director, Center for Energy Research, University of California at San Diego (2003-2011)

This National Construction Safety Team Advisory Committee provided technical advice during the Investigation and commentary on drafts of the Investigation reports prior to their public release. NIST has benefited from the work of many people in the preparation of these reports, including the National Construction Safety Team Advisory Committee. The content of the reports and recommendations, however, are solely the responsibility of NIST.

Public Outreach

During the course of this Investigation, NIST held public briefings and meetings (listed in Table P–2) to solicit input from the public, present preliminary findings, and obtain comments on the direction and progress of the Investigation from the public and the Advisory Committee.

NIST maintained a publicly accessible Web site during this Investigation at http://wtc.nist.gov. The site contained extensive information on the background and progress of the Investigation.

NIST's WTC Public-Private Response Plan

The collapse of the WTC buildings has led to broad reexamination of how tall buildings are designed, constructed, maintained, and used, especially with regard to major events such as fires, natural disasters, and terrorist attacks. Reflecting the enhanced interest in effecting necessary change, NIST, with support from Congress and the Administration, has put in place a program, the goal of which is to develop and implement the standards, technology, and practices needed for cost-effective improvements to the safety and security of buildings and building occupants, including evacuation, emergency response procedures, and threat mitigation.

Table P–2. Public meetings and briefings of the WTC Investigation.

Date	Location	Principal Agenda
June 24, 2002	New York City, NY	Public meeting: Public comments on the *Draft Plan* for the pending WTC Investigation.
August 21, 2002	Gaithersburg, MD	Media briefing announcing the formal start of the Investigation.
December 9, 2002	Washington, DC	Media briefing on release of the *Public Update* and NIST request for photographs and videos.
April 8, 2003	New York City, NY	Joint public forum with Columbia University on first-person interviews.
April 29–30, 2003	Gaithersburg, MD	NCST Advisory Committee meeting on plan for and progress on WTC Investigation with a public comment session.
May 7, 2003	New York City, NY	Media briefing on release of *May 2003 Progress Report.*
August 26–27, 2003	Gaithersburg, MD	NCST Advisory Committee meeting on status of the WTC investigation with a public comment session.
September 17, 2003	New York City, NY	Media and public briefing on initiation of first-person data collection projects.
December 2–3, 2003	Gaithersburg, MD	NCST Advisory Committee meeting on status and initial results and release of the *Public Update* with a public comment session.
February 12, 2004	New York City, NY	Public meeting on progress and preliminary findings with public comments on issues to be considered in formulating final recommendations.
June 18, 2004	New York City, NY	Media/public briefing on release of *June 2004 Progress Report.*
June 22–23, 2004	Gaithersburg, MD	NCST Advisory Committee meeting on the status of and preliminary findings from the WTC Investigation with a public comment session.
August 24, 2004	Northbrook, IL	Public viewing of standard fire resistance test of WTC floor system at Underwriters Laboratories, Inc.
October 19–20, 2004	Gaithersburg, MD	NCST Advisory Committee meeting on status and near complete set of preliminary findings with a public comment session.
November 22, 2004	Gaithersburg, MD	NCST Advisory Committee discussion on draft annual report to Congress, a public comment session, and a closed session to discuss pre-draft recommendations for WTC Investigation.
April 5, 2005	New York City, NY	Media and public briefing on release of the probable collapse sequence for the WTC towers and draft reports for the projects on codes and practices, evacuation, and emergency response.
June 23, 2005	New York City, NY	Media and public briefing on release of all draft reports for the WTC towers and draft recommendations for public comment.
September 12–13, 2005	Gaithersburg, MD	NCST Advisory Committee meeting on disposition of public comments and update to draft reports for the WTC towers.
September 13–15, 2005	Gaithersburg, MD	WTC Technical Conference for stakeholders and technical community for dissemination of findings and recommendations and opportunity for the public to make technical comments.
December 14, 2006	Teleconference	NCST Advisory Committee meeting on status of WTC 7 investigation and draft annual report to Congress, with a public comment session.
December 16, 2007	Teleconference	NCST Advisory Committee meeting on status of WTC 7 investigation and draft annual report to Congress, with a public comment session.

The strategy to meet this goal is a three-part, NIST-led, public-private response program that includes:

- A federal building and fire safety investigation to study the most probable factors that contributed to post-aircraft impact collapse of the WTC towers and the 47-story WTC 7 building, and the associated evacuation and emergency response experience.
- A research and development (R&D) program to (a) facilitate the implementation of recommendations resulting from the WTC Investigation, and (b) provide the technical basis for cost-effective improvements to national building and fire codes, standards, and practices that enhance the safety of buildings, their occupants, and emergency responders.
- A dissemination and technical assistance program (DTAP) to (a) engage leaders of the construction and building community in ensuring timely adoption and widespread use of proposed changes to practices, standards, and codes resulting from the WTC Investigation and the R&D program, and (b) provide practical guidance and tools to better prepare facility owners, contractors, architects, engineers, emergency responders, and regulatory authorities to respond to future disasters.

The desired outcomes are to make buildings, occupants, and first responders safer in future disaster events.

National Construction Safety Team Reports on the WTC Investigation

This report covers WTC 7, with supporting documentation of the techniques and technologies used in the reconstruction located in NIST NCSTAR 1-9 and NIST NCSTAR 1-9A. These two reports provide more detailed documentation of the Investigation findings and the means by which these technical results were achieved. As such, they are part of the archival record of this Investigation. Additional information regarding WTC 7 can be found in the previously published reports: NIST NCSTAR 1-1D, 1-1E, 1-1G, 1-3D, 1-3E, 1-4B, 1-4C, 1-4D, and 1-6A. The titles of the full set of Investigation publications are listed in Appendix B.

EXECUTIVE SUMMARY

WORLD TRADE CENTER BUILDING 7 (WTC 7)

WTC 7 was a 47 story office building located immediately to the north of the main WTC Complex. It had been built on top of an existing Consolidated Edison of New York electric power substation, which was located on land owned by The Port Authority of New York and New Jersey. On September 11, 2001, WTC 7 endured fires for almost seven hours, from the time of the collapse of the north WTC tower (WTC 1) at 10:28:22 a.m. until 5:20:52 p.m., when WTC 7 collapsed. This was the first known instance of the total collapse of a tall building primarily due to fires.

WTC 7 was unlike the WTC towers in many respects. It was a more typical tall building in the design of its structural system. It was not struck by an airplane. The fires in WTC 7 were quite different from those in the towers. Since WTC 7 was not doused with thousands of gallons of jet fuel, large areas of any floor were not ignited simultaneously. Instead, the fires in WTC 7 were similar to those that have occurred in several tall buildings where the automatic sprinklers did not function or were not present. These other buildings did not collapse, while WTC 7 succumbed to its fires.

THIS REPORT

This is the final report of the National Institute of Standards and Technology (NIST) investigation into the collapse of WTC 7, conducted under the National Construction Safety Team Act. The report is the result of an extensive, state-of-the-art reconstruction of the events that affected WTC 7 and eventually led to its collapse. Numerous facts and data were obtained, then combined with validated computer modeling to produce an account that captures the key features of what actually occurred. However, the reader should keep in mind that the building and the records kept within it were destroyed, and the remains of all the WTC buildings were disposed of before congressional action and funding was available for this Investigation to begin. As a result, there are some facts that could not be discerned, and thus there are uncertainties in this accounting. Nonetheless, NIST was able to gather sufficient evidence and documentation to conduct a full investigation upon which to reach firm findings and recommendations.

This report summarizes how NIST reached its conclusions. NIST complemented in-house expertise with private sector technical experts; accumulated copious documents, photographs, and videos of the disaster; conducted first-person interviews of building occupants and emergency responders; analyzed the evacuation and emergency response operations in and around WTC 7; performed computer simulations of the behavior of WTC 7 on September 11, 2001; and combined the knowledge gained into a probable collapse sequence. Extensive details on the reconstruction effort for WTC 7, the uncertainties, the assumptions made, and the testing of these assumptions are documented in NIST NCSTAR 1-9 and NIST NCSTAR 1-9A.

PRINCIPAL FINDINGS OF THE INVESTIGATION

The fires in WTC 7 were ignited as a result of the impact of debris from the collapse of WTC 1, which was approximately 370 ft to the south. The debris also caused some structural damage to the southwest

perimeter of WTC 7. The fires were ignited on at least 10 floors; however, only the fires on Floors 7 through 9 and 11 through 13 grew and lasted until the time of the building collapse. These uncontrolled fires had characteristics similar to those that have occurred previously in tall buildings. Their growth and spread were consistent with ordinary building contents fires. Had a water supply for the automatic sprinkler system been available and had the sprinkler system operated as designed, it is likely that fires in WTC 7 would have been controlled and the collapse prevented. However, the collapse of WTC 7 highlights the importance of designing fire-resistant structures for situations where sprinklers are not present, do not function (e.g., due to disconnected or impaired water supply, or are overwhelmed.

Eventually, the fires reached the northeast of the building. The probable collapse sequence that caused the global collapse of WTC 7 was initiated by the buckling of a critical interior column in that vicinity. This column had become unsupported over nine stories after initial local fire-induced damage led to a cascade of local floor failures. The buckling of this column led to a vertical progression of floor failures up to the roof and to the buckling of adjacent interior columns to the south of the critical column. An east-to-west horizontal progression of interior column buckling followed, due to loss of lateral support to adjacent columns, forces exerted by falling debris, and load redistribution from other buckled columns. The exterior columns then buckled as the failed building core moved downward, redistributing its loads to the exterior columns. Global collapse occurred as the entire building above the buckled region moved downward as a single unit. This was a fire-induced progressive collapse, also known as disproportionate collapse, which is defined as the spread of local damage, from an initiating event, from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it.

Factors contributing to the building failure were: thermal expansion occurring at temperatures hundreds of degrees below those typically considered in design practice for establishing structural fire resistance ratings; significant magnification of thermal expansion effects due to the long-span floors, which are common in office buildings in widespread use; connections that were designed to resist gravity loads, but not thermally induced lateral loads; and a structural system that was not designed to prevent fire-induced progressive collapse.

Within the building were emergency electric power generators, whose fuel supply tanks lay in and under the building. However, fuel oil fires did not play a role in the collapse of WTC 7. The worst-case scenarios associated with fires being fed by the ruptured fuel lines (a) could not have been sustained long enough, or could not have generated sufficient heat, to raise the temperature of the critical interior column to the point of significant loss of strength or stiffness, or (b) would have produced large amounts of visible smoke that would have emanated from the exhaust louvers. No such smoke discharge was observed.

Hypothetical blast events did not play a role in the collapse of WTC 7. NIST concluded that blast events did not occur, and found no evidence whose explanation required invocation of a blast event. Blast from the smallest charge capable of failing the critical column would have resulted in a sound level of 130 dB to 140 dB at a distance of at least half a mile. There were no witness reports of such a loud noise, nor was such a noise heard on the audio tracks of video recordings of the WTC 7 collapse.

There were no serious injuries or fatalities, because the estimated 4,000 occupants of WTC 7 reacted to the airplane impacts on the two WTC towers and began evacuating before there was significant damage to WTC 7. The occupants were able to use both the elevators and the stairs, which were as yet not damaged, obstructed, or smoke-filled. Evacuation of the building took just over an hour. The potential for injuries

to people leaving the building was mitigated by building management personnel holding the occupants in the lobby until they identified an exit path that was safe from the debris falling from WTC 1. The decision not to continue evaluating the building and not to fight the fires was made hours before the building collapsed, so no emergency responders were in or near the building when the collapse occurred.

The design of WTC 7 was generally consistent with the New York City Building Code of 1968 (NYCBC), with which, by policy, it was to comply. The installed thickness of the thermal insulation on the floor beams was below that required for unsprinklered or sprinklered buildings, but it is unlikely that the collapse of WTC 7 could have been prevented even if the thickness had been consistent with building code requirements. The stairwells were narrower than those required by the NYCBC, but, combined with the elevators, were adequate for a timely evacuation on September 11, 2001, since the number of building occupants was only about half that expected during normal business hours.

The collapse of WTC 7 could not have been prevented without controlling the fires before most of the combustible building contents were consumed. There were two sources of water (gravity fed overhead tanks and the city water main) for the standpipe and automatic sprinkler systems serving Floor 21 and above, and some of the early fires on those upper floors might have actually been controlled in this manner. However, consistent with the NYCBC, both the primary and back-up source of water for the sprinkler system in the lower 20 floors of WTC 7 was the city water main. Since the collapses of the WTC towers had damaged the water main, there was no water available (such as from the gravity-fed overhead tanks that supplied water to Floor 21 and above) to control those fires that eventually led to the building collapse.

Other than initiating the fires in WTC 7, the damage from the debris from WTC 1 had little effect on initiating the collapse of WTC 7. The building withstood debris impact damage that resulted in seven exterior columns being severed and subsequently withstood conventional fires on several floors for almost seven hours. The debris damaged the spray-applied fire resistive material that was applied to the steel columns, girders, and beams, only in the vicinity of the structural damage from the collapse of WTC 1. This was near the west side of the south face of the building and was far removed from the buckled column that initiated the collapse. Even without the structural damage, WTC 7 would have collapsed from fires having the same characteristics as those experienced on September 11, 2001. The transfer elements such as trusses, girders, and cantilever overhangs that were used to support the office building over the Con Edison substation did not play a significant role in the collapse of WTC 7.

RECOMMENDATIONS

Based on the findings of this Investigation, NIST identified one new recommendation (B, below) and reiterated 12 recommendations from the Investigation of the WTC towers. These encompass increased structural integrity, enhanced fire endurance of structures, new methods for fire resistant design of structures, improved active fire protection, improved emergency response, improved procedures and practices, and education and training.

The urgency of these recommendations is substantially reinforced by their pertinence to the collapse of a tall building that was based on a structural system design that is in widespread use.

The partial or total collapse of a building due to fires is an infrequent event. This is particularly true for buildings with a reliably operating active fire protection system such as an automatic fire sprinkler system. A properly designed and operating automatic sprinkler system will contain fires while they are small and, in most instances, prevent them from growing and spreading to threaten structural integrity.

The intent of current practice, based on prescriptive standards and codes, is to achieve life safety, not collapse prevention. However, the key premise of NIST's recommendations is that buildings should not collapse in infrequent (worst-case) fires that may occur when active fire protection systems are rendered ineffective, e.g., when sprinklers do not exist, are not functional, or are overwhelmed by the fire, or where the water supply is impaired.

Fire scenarios for structural design based on single compartment or single floor fires are not appropriate representations of infrequent fire events. Such events have occurred in several tall buildings resulting in unexpected substantial losses. Instead, historical data suggests that infrequent fires which should be considered in structural design have characteristics that include: ordinary combustibles and combustible load levels, local fire origin on any given floor, no widespread use of accelerants, consecutive fire spread from combustible to combustible, fire-induced window breakage providing ventilation for continued fire spread and accelerated fire growth, concurrent fires on multiple floors, and active fire protection systems rendered ineffective. The fires in WTC 7 had all of these characteristics.

The subjects of the NIST recommendations are as follows:

A. Development of methods for prevention of progressive collapse and for reliable prediction of the potential for complex failures in structural systems subjected to multiple hazards.

B (New). Explicit evaluation of the fire resistance of structural systems in buildings under worst-case design fires with any active fire protection systems rendered ineffective. Of particular concern are the effects of thermal expansion in buildings with one or more of the following features: long-span floor systems[1], connections not designed for thermal effects, asymmetric floor framing, and composite floor systems.

C. Evaluation and improvement of the technical basis for determining appropriate construction classification and fire rating requirements (especially for tall buildings), and making of related code changes.

D. Improvement of the technical basis for the standard for fire resistance testing of components, assemblies, and systems.

E. Broadening the scope of the "structural frame" approach to fire resistance ratings by including, as part of the structural frame, floor systems and other bracing members that are essential to the vertical stability of the building under gravity loads.

---

[1] Typical floor span lengths in tall office buildings are in the range of 12 m to 15 m (40 ft to 50 ft); this range is considered to represent long-span floor systems. Thermal effects (e.g., thermal expansion) that may be significant in long-span buildings may also be present in buildings with shorter span lengths, depending on the design of the structural system.

F. Enhancement of the fire resistance of structures by requiring a performance objective that uncontrolled building fires result in burnout without partial or global (total) collapse.

G. Development of performance-based standards and code provisions to enable the design and retrofit of structures to resist real building fire conditions, and the tools necessary to perform the building evaluations.

H. Enhancement of the performance and redundancy of active fire protection systems to accommodate higher risk buildings.

I. Establishment and implementation of codes and protocols for ensuring effective and uninterrupted operation of the command and control system for large-scale building emergencies.

J. Requirement that building owners to retain building documents over the entire life of the building.

K. Inclusion of all appropriate technical professionals in the building design team.

L Development and implementation of continuing education curricula for training building professionals in each others' skills and practices.

M. Development and delivery of training materials in the use of computational fire dynamics and thermostructural analysis tools.

Building owners, operators, and designers should immediately act upon the new recommendation (B). Industry should also partner with the research community to fill critical gaps in knowledge about how structures perform in real fires.

This page intentionally left blank.

Chapter 1
THE NEW YORK CITY WORLD TRADE CENTER BUILDING 7

1.1 THE WORLD TRADE CENTER COMPLEX

The New York City World Trade Center (WTC) complex was located in Lower Manhattan, just north of Wall Street, in the heart of the financial district. It was built by The Port of New York Authority, later to be renamed as The Port Authority of New York and New Jersey (The Port Authority, PANYNJ). Created in 1921, under a clause in the United States Constitution, to run the multi-jurisdictional commercial zones in the region, The Port Authority built and operated facilities on the banks of the Port of New York's waterways, the bridges to cross them, and the major metropolitan airports. It has the authority to obtain land by eminent domain, raise funds for its projects, and to construct under its own building code. Nonetheless, The Port Authority policy was to comply with the local building code in place at the time of building design, which, for the WTC complex, was the 1968 version of the New York City Building Code (NYCBC).

The original WTC complex consisted of six buildings (Figure 1–1). The two towers, WTC 1 (North Tower) and WTC 2 (South Tower), which provided the iconic appearance of the complex, were each 110 stories high, dwarfing the other skyscrapers in lower Manhattan. WTC 3, a Marriott Hotel, was 22 stories tall, WTC 4 (South Plaza Building) and WTC 5 (North Plaza Building) were each 9-story office buildings, and WTC 6 (U.S. Customs House) was an 8-story office building. These six buildings were built around a five acre Plaza. Construction began in 1968, with the first occupancy in 1970.

Commuter trains brought tens of thousands of workers and visitors to Manhattan from Brooklyn and New Jersey into a new underground station below the plaza. A series of escalators and elevators took the WTC employees directly to an underground shopping mall and to the Concourse Level of the towers.

1.2 WTC 7

1.2.1 The Edifice

In 1967, a Consolidated Edison of New York (Con Edison) substation had been built on Port Authority land on the north side of Vesey Street, between Washington Street on the west, West Broadway on the east, and Barclay Street on the north. This substation would distribute electrical power to Lower Manhattan. In designing the substation, provision was made for a future office tower by including structural capacity to carry the weight of both the substation and the future high-rise building.

Twenty years later, the high-rise building, designated WTC 7, was completed. The architectural design was performed by Emory Roth & Sons, P.C. The structural engineer of record was the Office of Irwin G. Cantor, and the mechanical engineer was Syska & Hennessy, P.C. Tishman Construction Corporation was the general contractor. The building was owned by Seven World Trade Company and Silverstein Development Corporation, General Partners.

This 47 story office building was located immediately to the north of the main WTC Complex, approximately 110 m (370 ft) from the north side of WTC 1 (Figure 1–1). It was connected to the WTC complex with a 37 m (120 ft) wide elevated plaza, known as the Promenade, at the 3rd floor level, and a 6.7 m (22 ft) wide pedestrian bridge, also at the 3rd floor level. Figure 1–2 is a photograph of the WTC site, showing the relationship of WTC 7 to the surrounding buildings.

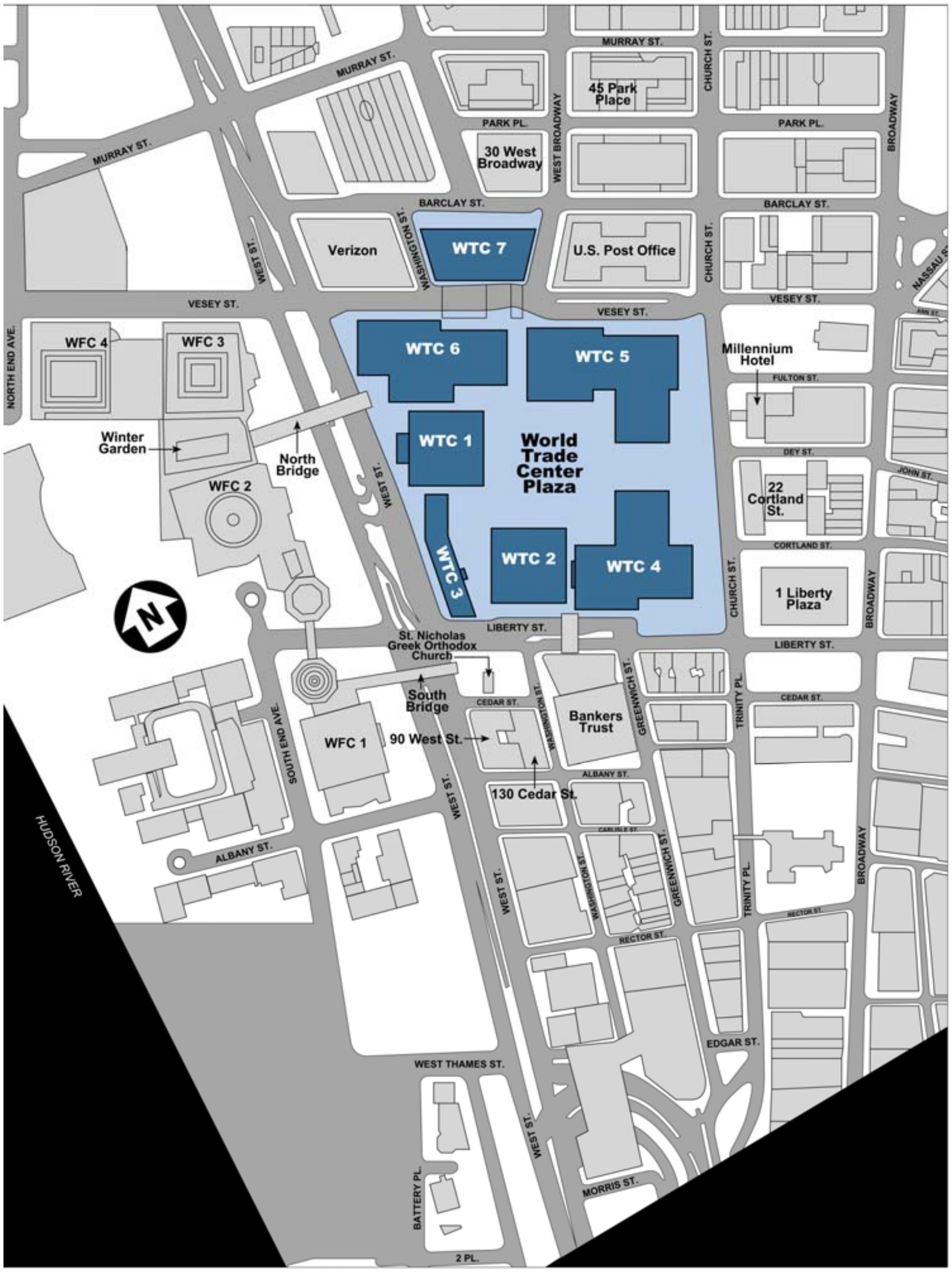


Figure 1–1. The World Trade Center in Lower Manhattan.

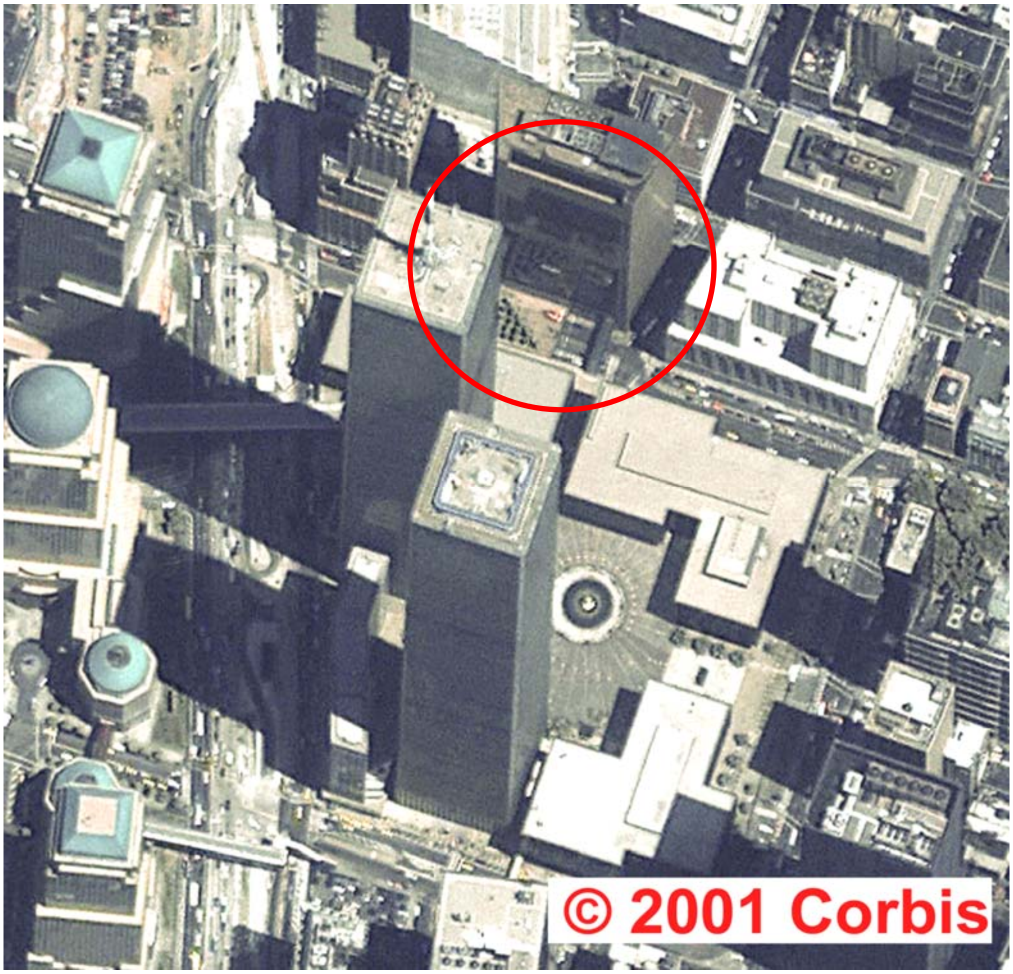


Figure 1–2. Photograph of the World Trade Center Complex, showing WTC 7.

1.2.2 The Con Edison Substation

The Con Edison substation was a steel-framed structure with cast-in-place concrete floors and walls. It was placed on the northern portion of the site and extended approximately 13 m (42 ft) north of the north facade of WTC 7, as shown in Figure 1–3. Its southerly boundary was irregular, but extended approximately two-thirds of the width of WTC 7. The Con Edison Substation was two stories in height, coinciding with the first two floors of WTC 7 (Figure 1–4). Details of the construction and the function of the substation can be found in NIST NCSTAR 1-9, Chapter 2 and Appendix A, respectively.

WTC 7 WTC 7 and the electrical substation were supported on caisson foundations, which were seated in the bedrock, approximately 20 m (60 ft) below the surface. Above the caissons were heavy grillages composed of built-up steel girders. The 2.5 m to 9 m (8 ft to 30 ft) distance between the caissons was braced by reinforced concrete walls with thicknesses varying from 1 ft to 2.5 ft. Many of the WTC 7 steel columns were embedded in these walls. The areas between the concrete walls were filled with compacted gravel fill and then covered with a concrete slab to form closed cells and bring the structure up to the required elevation. In some cases, the area was left unfilled and used to house fuel tanks.

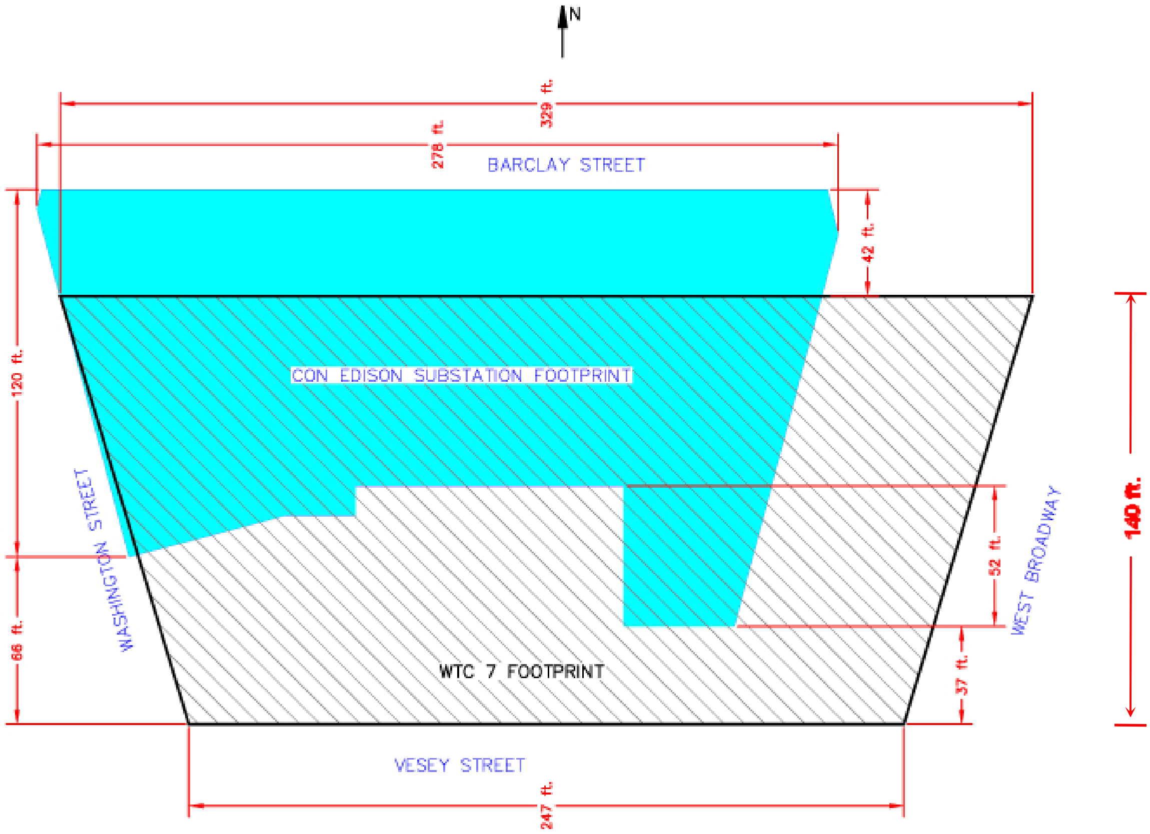


Figure 1–3. Footprints of the Con Edison substation and WTC 7.

Figure 1–4. Aerial view from the north side of WTC 7, showing the Con Edison substation.

(Photo taken prior to September 11, 2001.)

Source: Con Edison, used with permission

Within the substation were nine transformer vaults that housed the units that converted the 138 kV incoming power to 13.8 kV for transmission throughout Lower Manhattan. Access within the substation was provided by stairwells on the west side, in the center, and on the east side of the building. None of these stairs extended into the 47-story building above. In fact, concrete walls fully separated the substation from WTC 7.

1.2.3 The Structure

WTC 7 was an irregular trapezoid, approximately 100 m (329 ft) long on the north face and 75 m (247 ft) long on the south face, 44 m (144 ft) wide, and 186 m (610 ft) tall. The 47 story building contained approximately 200,000 m^2 (2 million ft^2) of floor area. A typical floor was similar in size to a football field. The gross floor area was about 75 percent of that contained in the Empire State Building. As shown in Figure 1–3, about half of WTC 7 rose outside the footprint of the Con Edison substation.

Structurally, WTC 7 consisted of four "tiers."

- The lowest four floors housed two two-story lobbies, one each on the center of the south side of the 1st and 3rd floors. The north side of the 1st and 2nd stories was the Con Edison substation. The remainder of the north, east, and west sides of these four stories was conference space, offices, a cafeteria, etc.
- Floors 5 and 6 were mechanical spaces. Within the volume bounded by the 5th floor slab and the 7th floor slab were three transfer trusses and a series of eight cantilever transfer girders. As their names indicate, these steel assemblies distributed the load of the upper floors of WTC 7 onto the structural frame of the Con Edison substation and the structure of the lowest four floors of WTC 7.
- Floors 7 through 45 were tenant floors, all structurally similar to each other. The exception was a reinforcing belt truss around Floors 22 and 23.
- The 46th and 47th floors, while mainly tenant floors, were structurally reinforced to support special loads, such as the cooling towers and the water tanks for fire suppression.

The structural frame was designed to distribute the weight of the building (gravity loads) and resist (lateral) wind loads. The frame included columns, floor assemblies, spandrel beams, girders, and transfer elements.

From the 7th floor to the 47th floor, WTC 7 was supported by 24 interior columns and 58 perimeter columns (numbered 1 through 57, plus 14A, which was located near the south end of the west face) (Figure 1–5). Twenty-one of the interior columns (numbered 58 through 78) formed a rectangular building core, which was offset toward the west of the building. The remaining three interior columns (79, 80, and 81) were particularly large, as they provided support for the long floor spans on the east side of the building.

In the final design of WTC 7, the layout of the columns did not align with the building foundation and the Con Edison columns. Therefore, a set of column transfers were constructed within the volume bounded by the 5th and 7th floor slabs. These are depicted in Figure 1–6, along with the numbers of the columns to which they connected.

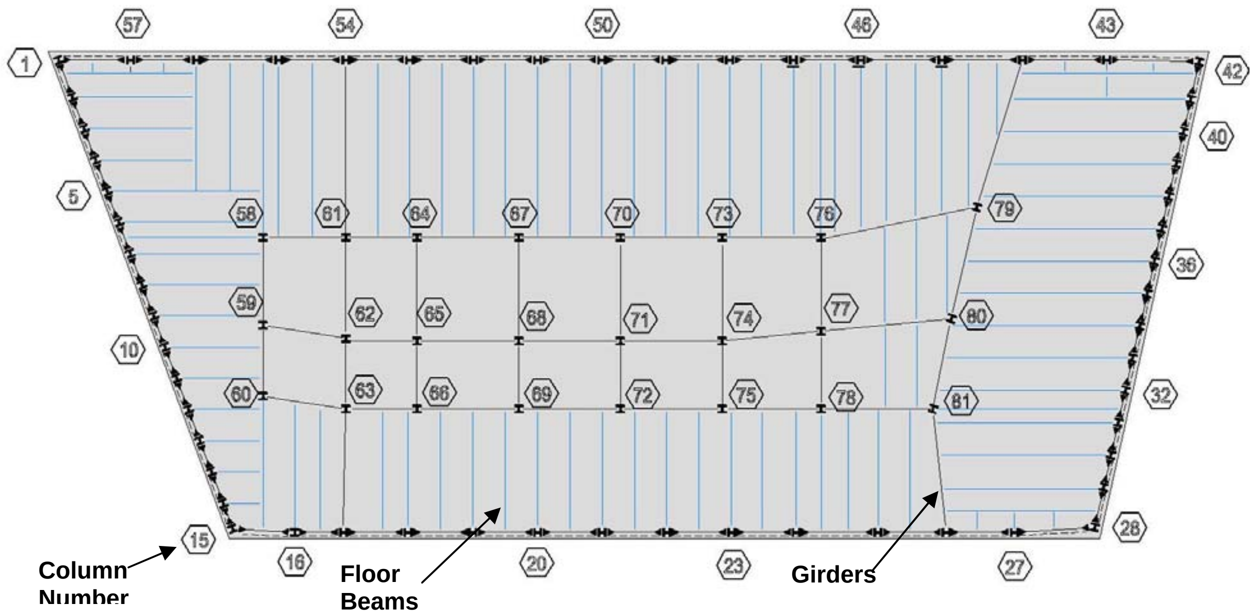


Figure 1–5. Typical WTC 7 floor showing locations of the columns, girders, and beams.

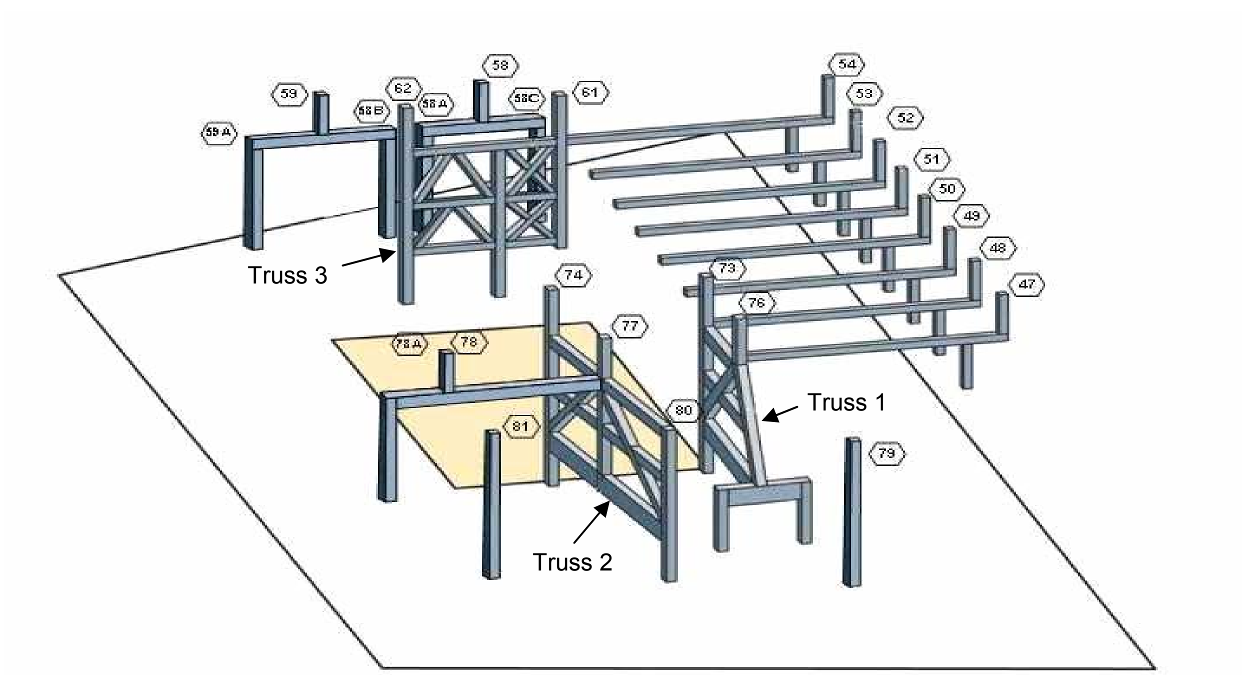


Figure 1–6. 3D schematic view of transfer trusses and girders between Floors 5 and 7.

The floor slabs were reinforced concrete of varying thickness. The 1st floor slab was 14 in. thick. The concrete on almost all of the other floors was poured on top of 3 in. deep corrugated metal decking. Floors 2, 3, 4, and 6 had a 6 in. total slab thickness; on Floor 5, the concrete was 14 in. thick; and on Floors 8 through 47, the concrete was 5.5 in. thick. On Floor 7, the south half of the floor had a poured

8 in. slab, and the north half had an 8 in. total slab thickness on a 3 in. deep metal deck. The floor slabs were supported by the structural floor framing shown in Figure 1–5. The floor beams were connected to the concrete deck by shear studs, which caused the floor beams and concrete slab to act together, or compositely. This type of floor system is thus referred to as a composite floor. The floor beams were framed into (connected to) girders with a variety of types of shear connectors[2], through which the floor beams transferred gravity loads from the floors to the girders. The girders also framed into the columns with a variety of types of shear connectors and transferred the gravity loads to the columns. Interior columns were connected with splice plates, welds and bolts. The exterior frame had moment connections in each face of the building.

1.2.4 Fire Protection

There were both passive and active fire protection systems in WTC 7 (NIST NCSTAR 1-9, Chapter 4). The former was in the form of sprayed fire-resistive material (SFRM) applied to the structural steel and to the underside of the metal floor decking. The latter comprised fire sensors and alarms, notification systems, automatic fire sprinklers, water supplies, and smoke management.

According to the 1968 version of the NYCBC and Local Law 16 (1984), a fully sprinklered high-rise building could follow the fire resistance requirements for Type 1C construction. For this construction category, columns were required to have a 2 h rating in the ASTM E 119 test; beams were required to have a 1½ h rating. The instructions to the bidders for the WTC 7 job were to bid on a 3 h rating for the columns and a 2 h rating for the fluted steel decking and floor support steel, which corresponded to the more stringent fire resistance requirements for Type 1B (unsprinklered) construction. These ratings were to be achieved by application of Monokote MK-5, a gypsum-based SFRM that contained a vermiculite aggregate. According to the Underwriters Laboratories (UL) Fire Resistance Directory (1983), these ratings required a thickness of 7/8 in. of Monokote MK-5 to be applied to the heavy columns, 1 7/8 in. to be applied to the lighter columns, ½ in. to be applied to the beams, and 3/8 in. to be applied to the bottom of the metal deck. Private inspectors found that the applied SFRM thicknesses were consistent with these values.

Within the building was an array of smoke detectors which, when triggered, would sound alarms on the floor of alarm and the floor above, provide an alarm and signal location to the Fire Command Station in the 3rd floor lobby, and transmit a signal to the fire department. There were barriers to smoke spread (in the form of walls and smoke dampers), as well as air movement equipment to exhaust the smoke.

WTC 7 contained a three-zone system of sprinklers and standpipes.

- Water to the low zone (1st floor through the 20th floor) came from the water main. The backup water also came from the water main via a supplemental pump.
- Water to the mid-level zone (21st floor through the 39th floor) was supplied from two large storage tanks located on the 46th floor. Backup water could be pumped from the water main.
- The sources of the primary and backup water supplies to the high zone (40th floor through the 47th floor) were the same as for the mid-level zone.

---

[2] Shear connections are designed to transfer only vertical gravity loads, whereas moment connections are designed to transfer loads and moments (forces resulting from bending of a beam) induced by both (vertical) gravity and (horizontal) wind.

The NYCBC requirement was for a 30 min water delivery duration at a delivered density of 0.10 gal/min-ft^2, and Investigation calculations determined that the installed system met these requirements. This would have been sufficient to control fires of four clusters of six workstations each, either all on one floor or single clusters on four floors.

These fire protection measures addressed the conventional approaches to preserving life safety. However, in the U.S., neither architectural nor structural engineering practice explicitly required (then or currently) an evaluation of the structural system response to heating (fires) as part of the building design.

1.2.5 The Workplace

Many of the roughly 8,000 people who worked in or visited WTC 7 on a given day would have arrived via trains that stopped in the large station under the main WTC complex. They could enter the first floor of the building through street-level doors along Vesey Street, Washington Street, and West Broadway. Alternatively, from the main WTC complex, they could cross Vesey Street via the Promenade or the covered pedestrian bridge and enter the 3rd floor lobby of the building.

Within the building core were 32 elevators, 28 of which would have taken them to their various offices. The floors that the elevators served are indicated in Figure 1–7.

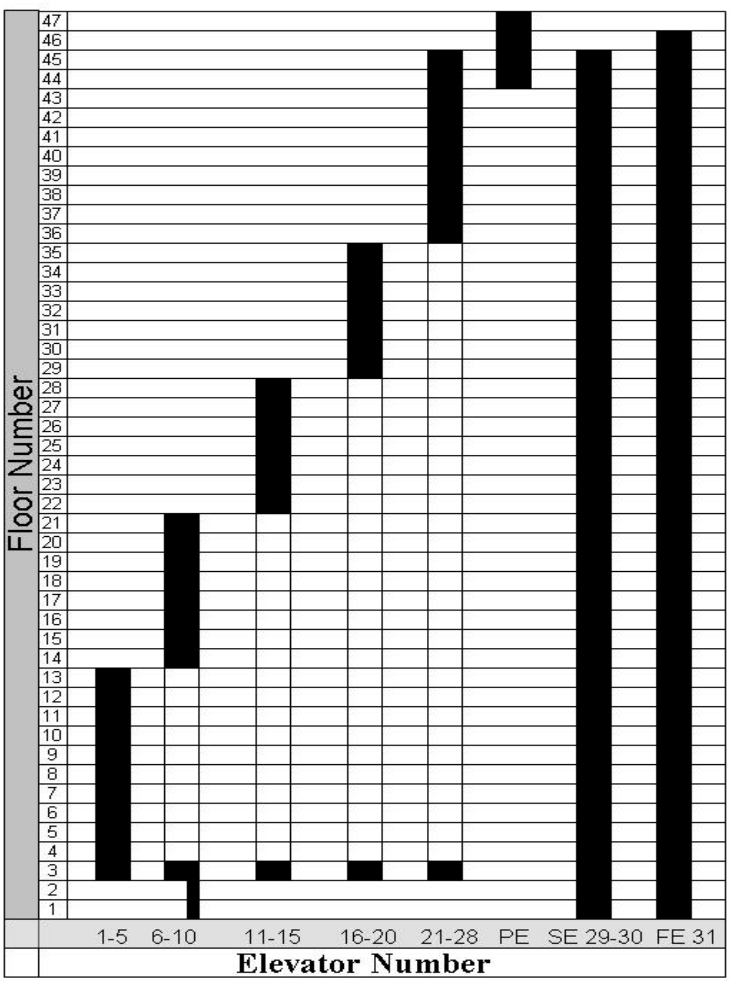


Figure 1–7. Schematic drawing of the elevators in WTC 7.

There were also two stairwells, each 56 in. to 58 in. wide. The west stairwell was entered through a side door on Washington Street. The stairs rose to the 5th floor, where there was a short transfer corridor. From there, the stairs were vertically continuous to the 47th floor. The east stairwell was entered from West Broadway and had transfer corridors on the 5th and 23rd floors, before continuing to the 47th floor.

WTC 7 was operated by Silverstein Properties, Inc., from the date of its completion. Table 1–1 indicates the tenants of WTC 7 as of September 11, 2001.

Table 1–1. Use of floors in WTC 7

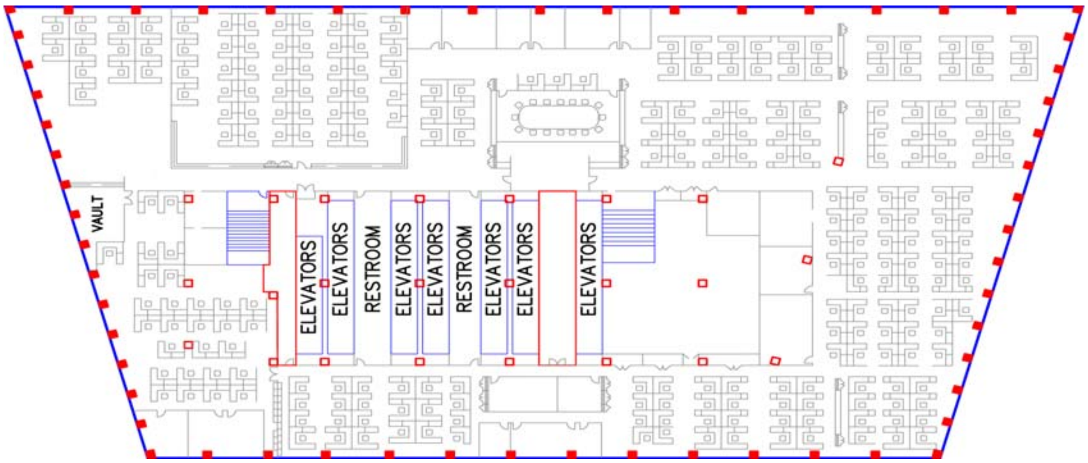
Floor(s)	Tenant or Function[a]
46, 47	Mechanical space, Salomon Smith Barney (SSB), now part of CitiGroup
26 through 45	Salomon Smith Barney
25	U.S. Internal Revenue Service, Department of Defense, Central Intelligence Agency
24	U.S. Internal Revenue Service
23	New York City Mayor's Office of Emergency Management (OEM)
22	Federal Home Loan Bank of New York
21	First State Management Group
19 through 21	The Hartford Insurance Company
18	Equal Employment Opportunity Commission, Teleport, Metropolitan Fiber Systems
15 through 17	Salomon Smith Barney
14	Vacant
13	U.S. Securities and Exchange Commission, Provident Financial Management, American Express
11, 12	U.S. Securities and Exchange Commission
10, 9	U.S. Secret Service
7, 8	American Express
5, 6	Mechanical floors
4	Meeting spaces, cafeteria
1 through 3	Lobbies, conference center

[a] Among those interviewed by the Investigation Team, there was limited recollection of the organizations occupying some of the floors, especially those occupying smaller spaces, and no one had copies of all the tenant leases..

1.2.6 The Combustible Contents

The layout of most of the floors featured clusters of workstations, or cubicles, throughout the space surrounding the building core (NIST NCSTAR 1-9, Chapter 3). Often, there were walled offices at the perimeter. The layout in Figure 1–8 is indicative of these floors. While there were almost certainly different types of workstations in the building, they were all fundamentally similar. Each cubicle typically was bounded on four sides by privacy panels, with a single entrance opening. Within the area defined by the panels was a self-contained workspace: desktop (almost always a wood product, generally with a laminated finish), file storage, bookshelves, carpeting, chair, etc. Presumably there were a variety of amounts and locations of paper, both exposed on the work surfaces and contained within the file cabinets and bookshelves.

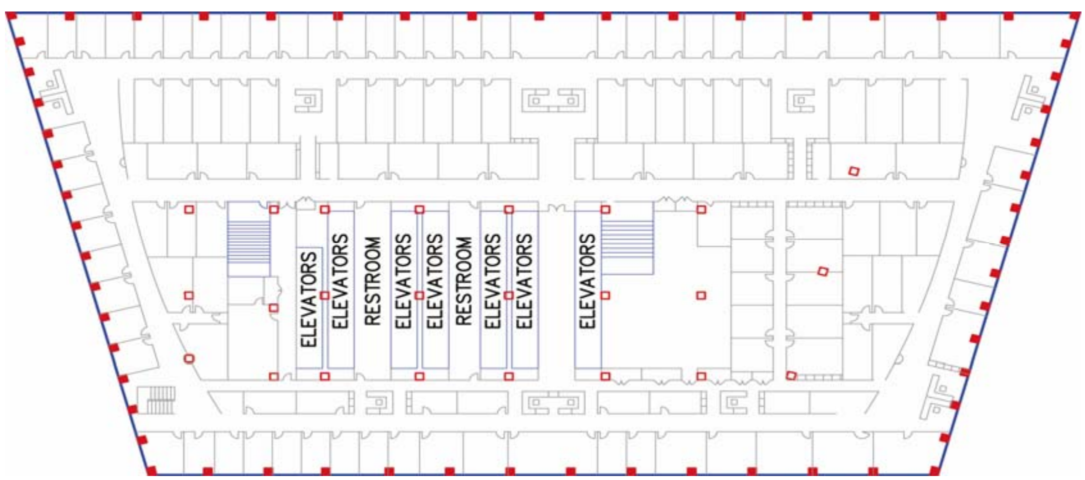
The combustible fuel load[3] for these open landscaped floors was dominated by the workstations. The architectural drawings showed densities of workstations similar to those on most of the fire floors in the WTC towers. The estimated combustible fuel load for these floors was about 20 kg/m^2 (4 lb/ft^2). Simulations of the fires with a higher combusted fuel load (NIST NCSTAR 1-9, Chapter 9) resulted in poor agreement with the observed fire spread rates.



Based on a floor plan and additional information from American Express.

Figure 1–8. Schematic of Floor 8.

On a number of other floors, the space was almost completely subdivided into individual offices. A typical layout is depicted in Figure 1–9.



Based on a floor plan and additional information from the U.S. Securities and Exchange Commission.

Figure 1–9. Schematic of Floor 11.

On the 11th and 12th floors, which will be seen later to have been the sites of significant and sustained fires, the mass of additional paper materials was described as very high. As indicated in NIST NCSTAR

[3] In the fire simulations, the entire combustible fuel load can be burned. In actuality, not all of, e.g., a wood desk is consumed. Thus, the combusted fuel loads estimated for these simulations are somewhat lower than the actual fuel loads in prior surveys of office buildings. (See NIST NCSTAR 1-5.)

1-9, Chapter 3, the Investigation Team estimated a combustible fuel load of approximately 32 kg/m^3 (6.4 lb/ft^2). Simulations of the fires with a lower combustible fuel load showed little effect on the rate of fire progression.

Unlike the case for the two WTC towers, there was no widespread spraying of jet fuel to ignite numerous workstations or offices simultaneously. Rather, in the earlier hours of the fires, the fire would have spread from one individual workstation or office to another. Thus, the fire spread would have been dependent on the office walls, the specific spacing of the cubicles, the ease of ignition of the furnishings, and their combustible mass.

There were emergency power generators in WTC 7 (NIST NCSTAR 1-1J). The diesel fuel for these generators was stored within and under WTC 7. The system properties are summarized in Table 1–2.

Table 1–2. Emergency power systems in WTC 7.

	Base Building System	Salomon Smith Barney (SSB) System	Mayor's OEM System
Fuel Storage Tank Capacities	Two 12,000 gal tanks	Two 6,000 gal tanks	Single 6,000 gal tank
Tank Locations	Below the loading dock	Below the loading dock	1st floor
Locations of Generator(s)	Two on 5th floor	Nine on the 5th floor	Three on the 7th floor
Day Tanks and Locations	Single 275 gal tank on the 5th floor	None[a]	Single 275 gal day tank on the 7th floor
Day Tank Pump Locations and Capacities	Two, on the 1st floor; 4.4 gal/min	Two circulating pumps on 1st floor, 70 gal/min	Two, on the 1st floor, 12 gal/min
Ambassador (U.S. Secret Service) Modification	Generator and 50 gal day tank on 9th floor; two pumps on the 1st floor, 2.4 gal/min		
American Express Modification	Generator and 275 gal day tank on 8th floor; two pumps on the 1st floor, 2.8 gal/min		

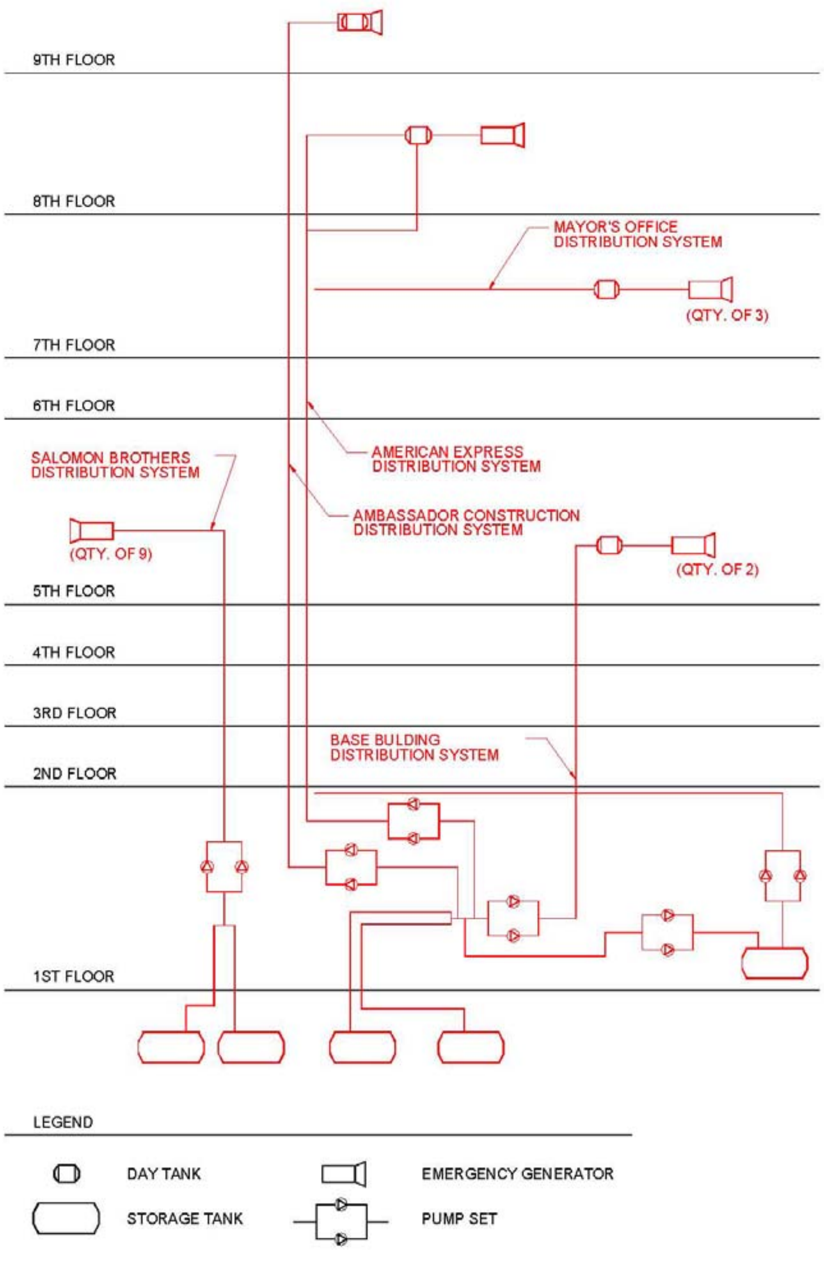
[a] The NYCBC had a limit of one day tank per floor. Since there was a day tank on the 5th floor for the base generators, the SSB system used a pressurized fuel distribution system, in which pumps continuously circulated fuel whenever the generators were running. There was enough fuel (35 gal) in the valve rig and piping on the 5th floor to start the diesel engines, which, in turn, would supply power to operate the circulating pumps.

Figure 1–10 depicts the locations of the electrical generators, the day tanks, and the fuel lines that connected them to the below-ground fuel tanks.

The base building tanks were full on September 11, 2001. Several months following the attacks on the WTC, a contractor recovered an estimated 23,000 gal of fuel from these tanks. NIST estimated that approximately 1000 gal ± 1000 gal was unaccounted. The fate of the fuel in the three day tanks is unknown, so NIST assumed they were full on September 11, 2001.

The fate of the fuel in the two tanks for the SSB system was also unknown. Thus, NIST assumed that all of the fuel would have been available to feed fires either at ground level or on the 5th floor.

No trace of the Mayor's OEM system tank or fuel was found. Since the pumps used to fill the day tank on the 7th floor would only have run when the low fuel switch came on, NIST assumed that all the fuel was available. This tank was enclosed in 4 h fire rated construction and was provided with a total flooding fire suppression system.



Source: NIST NCSTAR 1-1J.

Figure 1–10. Section view of fuel oil distribution components in WTC 7.

Chapter 2
THE ACCOUNT OF WTC 7

2.1 INTRODUCTION

Shortly before 9:00 a.m. on Tuesday, September 11, 2001, about 4,000 people were at work in WTC 7. This was about half of the roughly 8,000 people who worked there. It was the first day of school for many local children, and it also was a primary election day in New York. The weather was clear and comfortable, so some had taken time to do early morning errands.

At 8:46:30 a.m. EDT, five hijackers flew American Airlines Flight 11 (AA 11), a Boeing 767-200ER aircraft with 11 crew and 76 passengers on board, over the top of WTC 7 and into the north face of WTC 1. Moving at about 440 mph, the nose hit the exterior of the tower at the 96th floor. The aircraft cut a gash that was over half the width of the building and extended from the 93rd floor to the 99th floor. At 9:02:59 a.m., 16½ minutes after the first impact, five other hijackers flew United Airlines Flight 175, a Boeing 767-200ER with 9 crew and 51 passengers on board, into the south face of WTC 2 at about 540 mph, about 100 mph faster than AA 11. The center of the nose of the plane struck at the 81st floor slab. This entry wound stretched over nine floors, from Floor 77 to Floor 85 (NIST NCSTAR 1).

The account that follows is the result of an extensive, state-of-the-art reconstruction of the events that affected WTC 7 and eventually led to its collapse at 5:20:52 p.m. Numerous facts and data were obtained, then combined with validated computer modeling to produce an account that is believed to be close to what actually occurred. However, the reader should keep in mind that the building and the records kept within it were destroyed, and the remains of all the WTC buildings were disposed of before congressional action and funding was available for this Investigation to begin. As a result, there are some facts that could not be discerned, and thus there are uncertainties in this accounting. Nonetheless, NIST was able to gather sufficient evidence and documentation to conduct a full investigation upon which to reach firm findings and recommendations. The reconstruction effort for WTC 7, the uncertainties, the assumptions made, and the testing of these assumptions are documented in NIST NCSTAR 1-9.

2.2 ACTIVITY AT THE WTC 7 SITE

2.2.1 8:46 a.m. to 9:59 a.m. EDT

People throughout WTC 7 heard the boom of the aircraft hitting WTC 1, which was only about 110 m (350 ft) to the south. Lights flickered, the building shook, and some windows on the south side of WTC 7 were broken. However, few, if any, of the workers felt their lives were in immediate danger. This perception changed as the occupants became aware of the subsequent attacks on WTC 2 and the Pentagon, and people began using the elevators and stairs to leave the building. The elevators alone could have evacuated the building in about 20 min. The stairwells, although somewhat narrow for the maximum possible 14,000 occupants (estimated using the formula in the NYCBC), were more than adequate to evacuate roughly one-third of that number in the building that morning (NIST NCSTAR 1-9, Chapter 7).

At about 9:45 a.m., a manager from the OEM ordered the evacuation of WTC 7. It was not clear whether this order was broadcast over the public address system, because the building was already nearly empty.

Initially, as the occupants had tried to leave WTC 7, building officials kept them in the lobby for fear that they might be hurt by debris falling from WTC 1. The lobby quickly filled with evacuating WTC 7 occupants, occupants of WTC 5 and WTC 6 who had crossed Vesey Street using the Promenade and covered walkway, and injured people from WTC 1 in a medical triage post, established by the OEM. After the second aircraft was flown into WTC 2, the people in WTC 7 were directed down the turned-off escalators to the 1st floor lobby, out the loading dock doors on the west end of the south side of the building, and across Washington Street. There, they moved north under protection of scaffolding on the Verizon building. By the time WTC 2 collapsed at 9:59 a.m., all the building occupants who intended to leave WTC 7 had done so (NIST NCSTAR 1-9, Chapter 7).

The Fire Department of the City of New York (FDNY) had arrived on the scene by 8:50 a.m. and took control of the site, since this had been identified as a fire incident. Eventually, roughly 1,000 fire fighters would arrive. The New York City Police Department (NYPD) helicopters and the first of about 50 ground staff reached the site by 8:52 a.m. and began establishing a security perimeter around the WTC site. Port Authority Police Department (PAPD) and staff from the OEM were already present. There was extensive emergency response activity during this roughly 70 min interval. Aside from the medical triage unit set up in the WTC 7 lobby, most of their efforts were directed at the WTC towers (NIST NCSTAR 1-9, Chapter 6).

2.2.2 9:59 a.m. to 10:28 a.m. EDT

WTC 2 collapsed at 9:58:59 a.m. from the damage inflicted by the aircraft and the intense, multi-floor fires that followed. A few windows on lower floors of the south face of WTC 7 were broken, and dust and small debris were deposited in the 3rd floor lobby. None of the large pieces of debris from WTC 2 hit WTC 7 because of the large distance between the two buildings, and there was no evidence of structural damage to WTC 7.

When WTC 1 collapsed at 10:28:22 a.m., most of the debris landed in an area not much larger than the original WTC 1 building footprint. However, some fragments were forcibly ejected and traveled distances up to hundreds of meters. Pieces of WTC 1 hit WTC 7, severing six columns on Floors 7 through 17 on the south face and one column on the west face near the southwest corner. The damage to the building face is depicted in Figure 2–1. Based on photographic evidence, witness accounts, and engineering judgment, it is likely that the structural damage (steel and floor slabs) did not penetrate beyond the perimeter of the building core. At the southwest corner, the structural damage extended only about one-third of the distance from the exterior wall to the building core. The debris also broke a large number of windows on the south face. Compared to the airplane impact damage to the WTC towers, there was relatively little damage to the interior of WTC 7. For instance, damage to the sprayed fire resistive material (SFRM) was limited to the immediate vicinity of the WTC 1 debris impact. There was no superficial or structural damage to the north and east faces (NIST NCSTAR 1-9, Chapter 5).

The collapses of the two towers further focused the emergency responders' activities south of Vesey Street. FDNY moved its Command Post north on West Street towards Chambers Street, as a succession of FDNY officials took command of the incident.

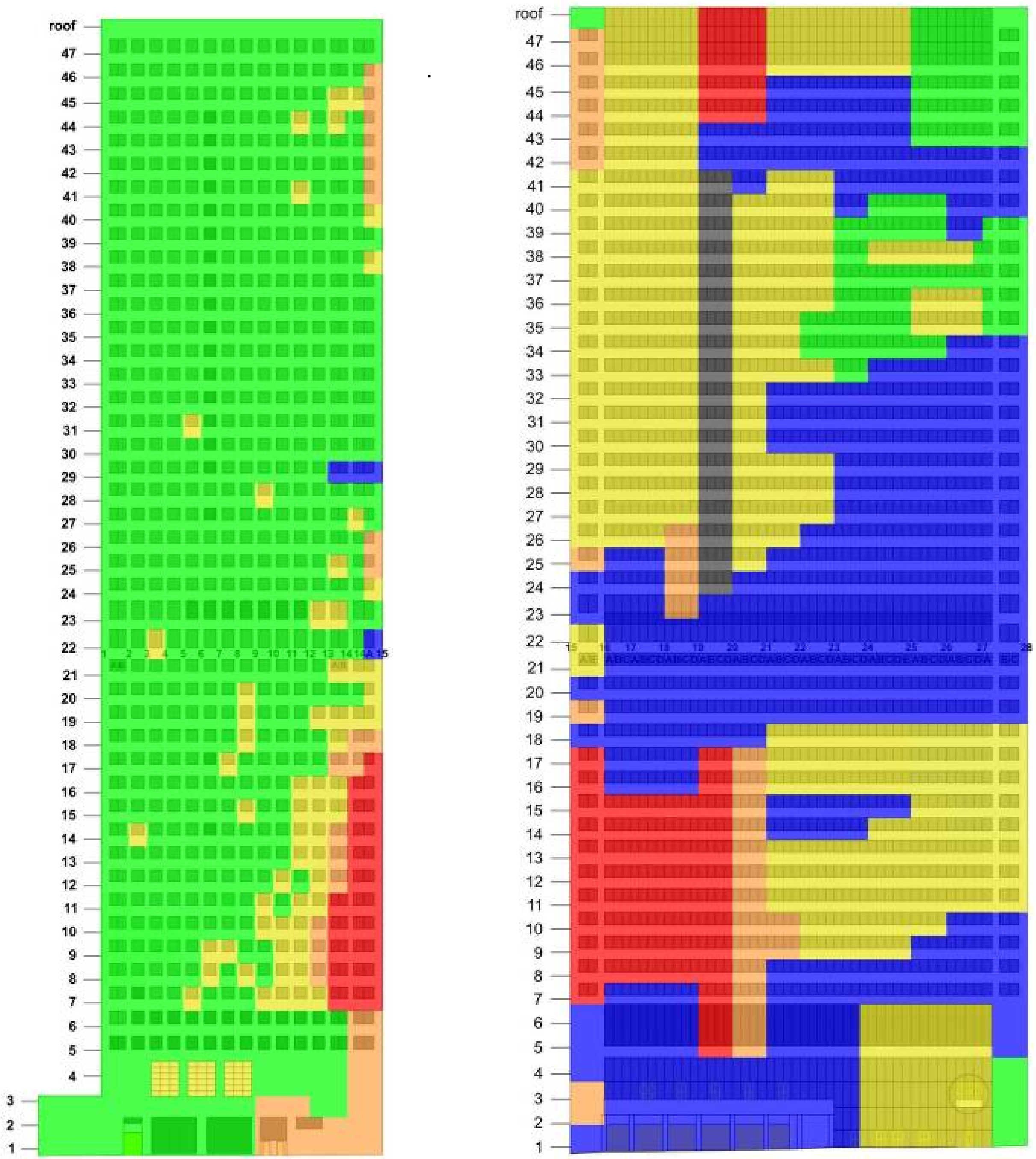


Figure 2–1. Observed damage to WTC 7 following the collapse of WTC 1.

West face (left) and south face (right)

The damage is color coded as follows: green (■)- no visible damage, yellow (■) – window glass broken, orange (■) – granite and underlying truss damage, red (■) – damage to exterior structural steel, gray (■) – possible structural damage, and blue (■) – not visible due to smoke, dust, and intervening buildings.

2.2.3 10:29 a.m. to 5:21 p.m. EDT

The emergency responders quickly recognized that WTC 7 had been damaged by the collapse of WTC 1. A number of fire teams entered WTC 7 to examine the damage, locate fires and possibly extinguish them, and search for occupants.

As early as 11:30 a.m., FDNY recognized that there was no water coming out of the hydrant system to fight the fires that were visible. With the collapses of the towers fresh in their minds, there was concern that WTC 7 too might collapse, risking the lives of additional firefighters. Within the next two hours, serious discussions were underway regarding the cessation of any efforts to save WTC 7, and the final order to cease was given at about 2:30 p.m. The Con Edison substation was shut down at 4:33 p.m. (NIST NCSTAR 1-9, Chapter 6).

2.3 PROGRESS OF THE FIRES IN WTC 7

General

Even though available images showing fires in WTC 7 did not allow the detailed description of fire spread that was possible for the WTC towers, there was sufficient information to derive general descriptions of fire ignition and spread on various floors of the building (NIST NCSTAR 1-9, Chapter 5). It must be kept in mind that the fire observations were based on images of the exterior faces, which provided little indication about the behavior of fires well removed from the exterior walls. It is likely that much of the burning took place beyond the views of the windows. Relatively little smoke was seen emanating from the windows on the north face, even when flames were observed, indicating that the hot combustion products were not exhausting through the nearest openings, but instead were passing through the building interior to other exits. The wind direction was from the north, and since there would have been office furnishings spread across the tenant spaces, some of the air would have penetrated to the building interior and supported combustion of the furnishings located there. Features of this interior burning were reconstructed from the computer simulations of the fires, as described in NIST NCSTAR 1-9, Chapter 9.

Most likely, the WTC 7 fires began as a result of the impact of debris from the collapse of WTC 1 at about 10:29 a.m. Soon after that, there were numerous vehicles around WTC 7 that were on fire, presumably ignited by burning debris from the tower. It is likely that nascent fires were also growing within WTC 7 around the same time, although direct visual evidence for fires in the building was not available until around noon. From the fire spread patterns, it is also likely that the fires began near the western half of the south face.

Fires broke out on at least 10 floors of WTC 7, all near the damaged southwest corner of the building (NIST NCSTAR 1-9, Chapter 5). They were typically observed as single floor fires, and observations supported a single point of ignition on any given floor. Unlike the WTC towers, there was no dispersion of jet fuel in WTC 7 causing simultaneous fire initiation over extensive areas of a single floor or over multiple adjacent floors.

The early fire on each floor was small, probably involving a single cubicle or office. On the floors which were mostly furnished with clusters of cubicles (such as Floors 7 and 8), the initial fire spread would have

been by flame contact with an adjacent cubicle within the cluster. Once a cluster was burning, a nearby cubicle, across an aisle, could have been ignited by thermal radiation from the flames. By the time this second cluster was fully involved, the prior cluster would have passed its peak burning rate. The path of the fires would likely have jumped from cluster to cluster, meandering toward the windows, toward the building core, or parallel to the façade. Eventually, the upper air layer over enough of the large open space would have become hot enough for the thermal radiation from the hot air to have heated and ignited multiple cubicles simultaneously, leading to faster fire growth.

On those floors that were mostly subdivided into offices (such as Floors 11 and 12), the fire would have grown within a single office, reaching flashover[4] in several minutes. After about 15 min, the ceiling tile system would have failed from the heat, and the hot air would have flowed over the office wall. Soon the hot air would fail the ceiling of an adjacent office, and eventually the thermal radiation would ignite the contents in this office. Fire spread would have been similar for offices separated by a corridor, although this would have taken longer, since the hot air would have to travel further and would be cooling along the way.

Between 12:10 p.m. and 1:00 p.m., there were fires at the southwest corners of the 19th, 22nd, 29th, and 30th floors. These fires grew large enough to break glass from nearby windows, but did not spread far before dying out. These fires might have also burned along the south sides of the floors, where they would not have been seen, due to limited imagery and smoke obscuration. It is possible that the fires on the 22nd, 29th, and 30th floors were controlled by automatic sprinklers, whose water came from the storage tanks on the 46th floor. At any rate, after about 1:00 p.m., there was no evidence of fires on these floors on the east, north, or west faces of the building.

Between roughly 2:00 p.m. and the collapse of WTC 7 at 5:20:52 p.m., fires were observed spreading on the 7th floor through the 13th floor, with the exception of the 10th floor. Since the collapses of the towers had resulted in the loss of city water that was the sole supply for the automatic sprinkler system on the lower 20 floors of WTC 7, these fires continued to spread unabated. All of these fires reached the northeast sector of the building between approximately 3:00 p.m. and 4:00 p.m. The intensities of the fires on the 11th, 12th, and 13th floors were higher than those on the 7th, 8th, and 9th floors because of the higher loading of combustibles and a larger burning area. There was also a small fire on the north side of the vacant 14th floor shortly before the collapse of the building. The following sections describe the timing and paths of these fires (NIST NCSTAR 1-9, Chapter 5). There was no visual evidence of fires on other floors, other than near the debris-damaged southwest corner of the building.

7th Floor

The fire spread on this floor was clockwise. Shortly after 2:00 p.m., there was a fire on the west side of the 7th floor, spreading north along the west face. The fire turned the northwest corner and by 3:00 p.m. was spreading east across the north face. Around 3:15 p.m., the fire, which had passed the midpoint of the north face, stopped and died down. About an hour later, the fire appeared a little farther to the east, then died down by 4:40 p.m. Although no further images were available, it is likely that the fire continued to burn toward the east.

---

[4] Flashover is the point in an enclosure fire when the fire changes (often abruptly) from being a local fire, perhaps involving one or two combustibles, to becoming a fire involving virtually all the combustibles.

8th Floor

The 8th floor fire also spread clockwise. At about 3:40 p.m., a broad fire was first seen spreading east from the center of the north face. A few minutes later, there was a fire on the north end of the west face, suggesting that the fire had burned at the interior of the floor, initially bypassing the northwest corner, then burning back to that corner after the fire became established on the north face. The fire on the north face spread rapidly eastward, reaching the east face around 3:55 p.m., and then burned intensely on the east face. Soon after 4:00 p.m., the observable burning near the center of the north face had died down.

9th Floor

There were no indications of fire on the 9th floor until shortly before 4:00 p.m., when a small fire appeared on the west side of the north face. The fire grew rapidly and spread to the east, reaching the midpoint of the north face by around 4:10 p.m. Ten minutes later, the fire was halfway to the northeast corner, but by 4:38 p.m., there were only spot fires visible, located on the east side of the north face.

11th Floor

The fire on this floor generally spread counterclockwise. Fire was first observed at 2:08 p.m. at the south end of the east face. Over the next 20 min, the fire spread slowly northward to the midpoint of the east face. Over the next two hours, images showed no burning. At 5:09 p.m., the fire reappeared near the center of the north face, spreading slowly to the west and not reaching the northwest corner when WTC 7 collapsed at 5:21 p.m. In the meantime, at 4:38 p.m., a fire appeared spreading east from the center of the north face, once again suggesting that the prior burning had progressed along the interior of the building before backtracking to combust furnishings near the perimeter. By 4:52 p.m., the observable flames in the area had died down.

12th Floor

The fire on the 12th floor followed a path similar to that of the fire on the 11th floor, but with different timing. Fire was first seen on the 12th floor at 2:08 p.m., toward the south end of the east face. Further south on this face, the window glass was still intact, indicating that this fire had burned in the building interior as it turned the southeast corner.

By around 2:30 p.m., the visible flames had diminished, but the fire had spread both south into the southeast corner and north, reaching two-thirds of the way to the northeast corner. By 3:00 p.m., the fire had spread internally past the northeast corner and onto the north face. In less than 15 min, the fire simultaneously spread rapidly to the east to engulf the northeast corner of the floor and more slowly westward about one-third of the way across the north face. The fire continued spreading westward in starts and stops, approaching the northwest corner of the floor around 3:45 p.m. At around 5:00 p.m., the fire had reached the northwest corner.

13th Floor

Like the fires on the 11th and 12th floors, this fire also moved counterclockwise. Fire was seen at about 2:30 p.m. on the east face of the floor. Somewhat later, smoke and flames were coming from windows

across much of the east face. Around 3:41 p.m., the fire had turned the northeast corner and was one-fourth of the way across the north face. Soon after 4:00 p.m., flames had reached at least to the midpoint of the north face; and at 4:38 p.m., the fires to the east had died down to the point where they could no longer be observed. Around 5:00 p.m., there was intense burning to the west of the center of the north face. A couple of minutes prior to the collapse of the building at 5:20:52 p.m., flames jetted from windows in the same area, indicating that there had been fire toward the interior of the floor.

14th Floor

A fire was seen briefly on the north face, about halfway between the midpoint and the northeast corner, at 5:03 p.m. No fire was evident in images taken a few minutes before and a few minutes after this time.

2.4 THE PROBABLE COLLAPSE SEQUENCE

The following is the NIST account of how the fires in WTC 7 most likely led to the building's collapse.

The collapse of WTC 1 damaged seven exterior columns on the lower floors of the south and west faces of WTC 7 and initiated fires on 10 floors between Floors 7 and 30. It also ignited fires on at least 10 floors, and burned out of control on Floors 7 to 9 and 11 to 13. Fires on these six floors grew and spread since they were not extinguished either by the automatic sprinkler system or by FDNY, because water was not available. Fires were generally concentrated on the east and north sides of the northeast region beginning at about 3 p.m. to 4 p.m.

As the fires progressed, some of the structural steel began to heat. According to the generally accepted test standard, ASTM E-119, the fire resistance rating for a steel column or floor beam derives from the time at which, during a standard fire exposure, the average column temperature exceeds 538 °C (1000 °F) or the average floor beam temperature exceeds 593 °C (1100 °F). These are temperatures at which there is significant loss of steel strength and stiffness. Due to the effectiveness of the SFRM, the highest column temperatures in WTC 7 only reached an estimated 300 °C (570 °F), and only on the east side of the building did the floor beams reach or exceed about 600 °C. The heat from these uncontrolled fires caused thermal expansion of the steel beams on the lower floors of the east side of WTC 7, damaging the floor framing on multiple floors.

The initiating local failure that began the probable WTC 7 collapse sequence was the buckling of Column 79. This buckling arose from a process that occurred at temperatures at or below approximately 400 °C (750 °F), which are well below the temperatures considered in current practice for determining fire resistance ratings associated with significant loss of steel strength. When steel (or any other metal) is heated, it expands. If thermal expansion in steel beams is resisted by columns or other steel members, forces develop in the structural members that can result in buckling of beams or failures at connections.

Fire-induced thermal expansion of the floor system surrounding Column 79 led to the collapse of Floor 13, which triggered a cascade of floor failures. In this case, the floor beams on the east side of the building expanded enough that they pushed the girder connecting Columns 79 and 44 to the west on the 13th floor. (See Figure 1–5 for column numbering and the locations of girders and beams.) This movement was enough for the girder to lose its connection to Column 79.

The displaced girder and other local fire-induced damage caused Floor 13 to collapse, beginning a cascade of floor failures down to the 5th floor (which, as noted in Section 1.2.3, was much thicker and stronger). Many of these floors had already been at least partially weakened by the fires in the vicinity of Column 79. This left Column 79 with insufficient lateral support in the east-west direction. The column buckled eastward, becoming the initial local failure for collapse initiation.

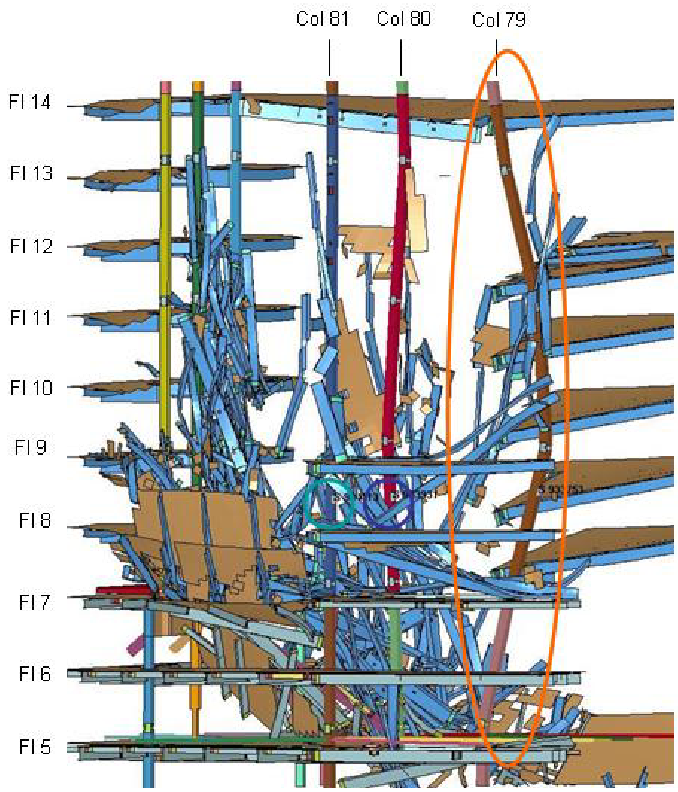


Figure 2–2. Eastward buckling of Column 79, viewed from the southeast.

The upper section of Column 79 began to descend. The cascading failures of the lower floors surrounding Column 79 led to increased unsupported length in, falling debris impact on, and loads being re-distributed to adjacent columns; and Column 80 and then Column 81 buckled as well. All the floor connections to these three columns, as well as to the exterior columns, failed, and the floors fell on the east side of the building. The exterior façade on the east quarter of the building was just a hollow shell.

The failure then proceeded toward the west. Truss 2 (Figure 1–6) failed, hit by the debris from the falling floors. This caused Column 77 and Column 78 to fail, followed shortly by Column 76. Each north-south line of three core columns then buckled in succession from east to west, due to loss of lateral support from floor system failures, to the forces exerted by falling debris, which tended to push the columns westward, and to the loads redistributed to them from the buckled columns. Within seconds, the entire building core was failing.

The global collapse of WTC 7 was underway. The shell of exterior columns buckled between the 7th and 14th floors, as loads were redistributed to these columns due to the downward movement of the building core and the floors. The entire building above the buckled-column region then moved downward as a single unit, completing the global collapse sequence.

Chapter 3
DERIVING THE PROBABLE COLLAPSE SEQUENCE

3.1 GATHERING OF EVIDENCE

Similar to the investigation into the collapse of the WTC towers, data for WTC 7 were collected from a number of sources and reviewed. Much of the information on WTC 7 was gathered and published during the reconstruction of the collapses of the towers. Comparison of the various building codes in use at the time of construction was the subject of NIST NCSTAR 1-1E. Details of the fire safety provisions and systems were published in NIST NCSTAR reports 1-1D, 1-1G, 1-1I, 1-4B, 1-4C, and 1-4D. The emergency power systems were described in NIST NCSTAR 1-1J. The properties of the structural steels used in the construction were the subject of NIST NCSTAR 1-3D and NIST NCSTAR 1-3E. The SFRM properties were presented in NCSTAR 1-6A. Much of the activities of the emergency responders was reported in NIST NCSTAR 1-8. A description of the collection and cataloguing of the photographic and videographic evidence appeared in NIST NCSTAR 1-5A. This included visuals of debris impact damage and fire spread subsequent to collapse of the WTC towers. Additional imagery was collected subsequent to the previously reported library. While not as plentiful as the imagery for the WTC towers, the cumulative WTC 7 evidence was sufficient to guide the reconstruction of the day's events.

As with the WTC towers, much of the information specific to the WTC 7 building construction was lost with the destruction of the WTC site. Nonetheless, copious information was obtained from drawings and specifications, reports, and available records from The Port Authority, Silverstein Properties (SP), and a number of contractors that had worked on the design, construction, or modifications of WTC 7. The documents included erection and fabrication shop drawings of the building, which provided detailed information about the floor and column connections. Information and documents regarding the layout of the building interior were obtained from WTC 7 tenants. Staff of the occupying organizations and SP staff were also interviewed to gain additional insights into the layout, furnishing, and overall fuel loads. Additional interviews with emergency responders and building officials, along with tapes of radio transmissions from September 11, 2001, provided accounts of the human activity inside the building and around the WTC site.

3.2 THE LEADING HYPOTHESIS

Based on observations and analyses of photographic and video records, critical study of steel framing, and simplified and detailed analyses to investigate possible failure modes that could lead to an initiating event, NIST developed the following collapse hypothesis, beginning in 2004:

- The conditions that led to the collapse of WTC 7 arose from fires, perhaps combined with structural damage that followed the impact of debris from the collapse of WTC 1. The fires were fed by ordinary office combustibles.

- The fires on Floors 7 through 13 heated the building structure. Being lighter than the columns and with thinner SFRM, the floor beams, floor slabs, and connections heated more quickly and to

higher temperatures. The elevated temperatures in the floor elements led to their thermal expansion, sagging, and weakening, which resulted in failure of floor connections and/or buckling of floor beams.

- Sufficient breakdown of connections and/or beams resulted in damage to at least one of the critical columns supporting a large-span floor bay on the eastern side of the building on or below Floor 13. This was the initiating event of the collapse.
- The initial local failure progressed upward to the east penthouse. As the large floor bays became unable to redistribute the loads, the interior structure below the east penthouse descended.
- Triggered by damage due to the vertical failure, the failure progressed westward in the region of Floors 7 through 14, where the floor slabs had been weakened by fires. This resulted in a disproportionate collapse of the entire structure.

The Investigation Team then proceeded to examine this hypothesis more closely and to consider possible alternative collapse initiating processes.

3.3 HYPOTHETICAL BLAST SCENARIOS

Considerable effort was expended to compile evidence and to determine whether intentionally set explosives might have caused the collapse of WTC 7 (NIST NCSTAR 1-9, Appendix D). As a minimum, the explosive material would have had to cause sufficient damage to a critical column or truss that it became unable to carry its service load or that a lateral deflection would cause it to buckle.

Six combinations of explosive location and column/truss and two implementation scenarios were considered. In the first scenario, there was ample time for optimized preparation of the structure (including possible preliminary cutting of structural members) and use of the minimum mass of explosives. In the second scenario, the explosion was to be effected in the shortest possible time, which was to be no more than a 7 h to 8 h time frame.

SHAMRC, a software program that is used for analysis of explosive detonations, shock propagation and structure loads due to blast and fragments, was used to simulate pressure histories from the hypothetical blasts. The pressure histories were then used to determine whether windows would have broken, which would have provided visible evidence of a charge detonation to observers outside the building. SHAMRC has a proven record of accuracy for explosive weights of less than 500 g (1 lb) to more than 4×10^6 kg (4,000 tons). A validated Shard Fly-Out Model (SFOM) was used to predict window breakage. Simulations were performed for differing degrees of partitioning of a tenant floor.

Attention focused on a single hypothetical blast scenario explosive location. This involved preliminary cutting of Column 79 and the use of 4 kg (9 lb) of RDX explosives in linear shaped charges. The other scenarios would have required more explosives, or were considered infeasible to carry out without detection. Calculations were also performed for a lesser charge size of 1 kg (2 lb) to evaluate threshold explosive requirements for window fragility.

Figure 3–1 shows the results for the two shaped charges applied to Column 79 on a tenant floor that was highly partitioned, such as Floor 12. Nearly all the windows on the northeast section of the blast floor

would have been broken, even by the smaller charge. Simulations for open landscaped floors led to more extensive window breakage.

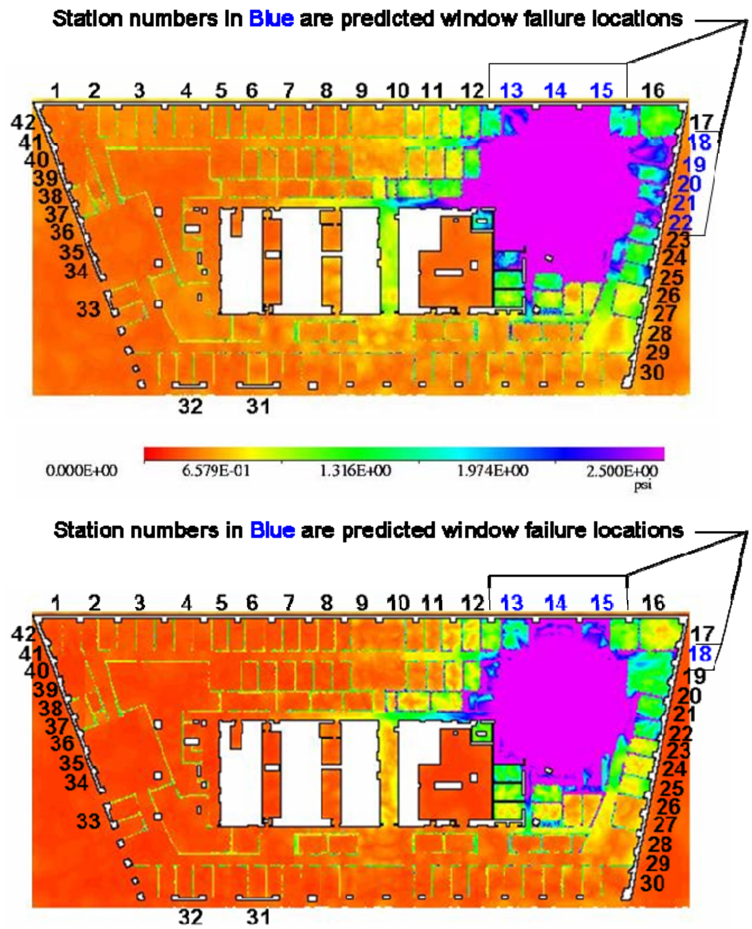


Figure 3–1. Peak overpressure and broken window locations.

Top: 9 lb shaped charge; bottom: 2 lb charge.

The actual window breakage pattern on the visible floors on September 11, 2001 (NIST NCSTAR 1-9, Chapter 5) was not at all like that expected from a blast that was even 20 percent of that needed to damage a critical column in WTC 7. The visual evidence did not show showing such a breakage pattern on any floor of WTC 7 as late as about 4:00 p.m. or above the 25th floor at the time of the building collapse initiation. Views of the northeast corner at the time of the collapse were obstructed by other buildings.

The window breakage would have allowed the sound of a blast to propagate outward from the building. NLAWS, a validated acoustic wave propagation software program, was used to predict the propagation of the sound of the hypothetical blasts. The calculations showed that all the hypothetical blast scenarios and charge sizes would have broadcast significant sound levels from all of the building faces. For instance, if propagation were unobstructed by other buildings, the sound level emanating from the WTC 7 perimeter openings would have been approximately 130 dB to 140 dB at a distance of 1 km (0.6 mile) from WTC 7. This sound level is consistent with standing next to a jet plane engine and more than 10 times louder than being in front of the speakers at a rock concert. The sound from such a blast in an urban setting would have been reflected and channeled down streets with minimum attenuation. The hard building exteriors would have acted as nearly perfect reflectors, with little to no absorption. The sound would have been attenuated behind buildings, but this would also have generated multiple echoes. These echoes could have

extended the time period over which the sound could have been detected and could possibly have had an additive effect if multiple in-phase reflections met. However, the soundtracks from videos being recorded at the time of the collapse did not contain any sound as intense as would have accompanied such a blast (NIST NCSTAR 1-9, Chapter 5). Therefore, the Investigation Team concluded that there was no demolition-type blast that would have been intense enough to lead to the collapse of WTC 7 on September 11, 2001.

3.4 THE FOUR-STEP SIMULATION PROCESS

3.4.1 Technical Approach

To test the working hypothesis and to reconstruct the probable collapse sequence for WTC 7, the Investigation Team supplemented the information available from the photographic and videographic evidence, eyewitness accounts, and personal interviews with computer simulations. The analyses accounted for the debris-impact damage, the growth and spread of fires, the heating and thermal weakening of structural components, and the progression of local structural failures that led to the collapse of the building.

Figure 3–2 is a flow chart of the four-step analysis sequence and inter-dependencies for the reconstruction of the WTC 7 collapse. Four models were used, as described in Sections 3.4.2 through 3.4.5.

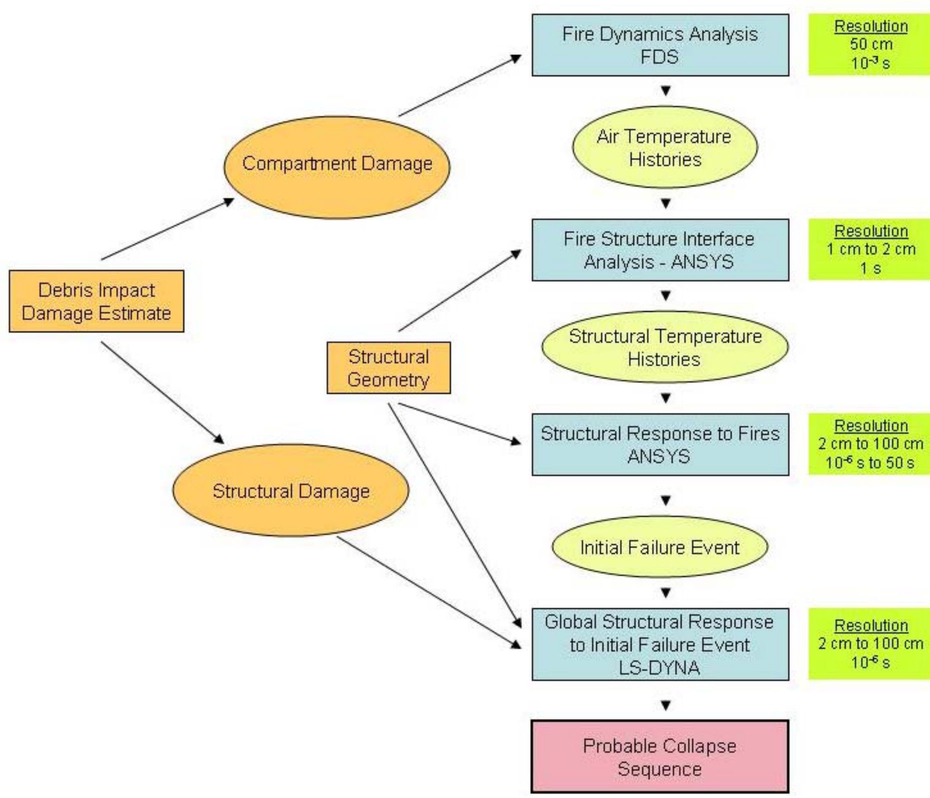


Figure 3–2. WTC 7 analysis sequence and interdependencies.

Similar to the analyses conducted for the WTC towers, the analyses of WTC 7 continued to advance the current state of the art and tested the limits of computational capabilities. The unprecedented complexity and sophistication of these analyses required the use of various strategies for managing the computational demands while adequately capturing the essential physics of the problem. The uncertainties, the assumptions made, and the testing of these assumptions are documented in NIST NCSTAR 1-9. Beyond the assumptions that were considered in the collapse analysis of the WTC towers, four additional significant areas of uncertainty influenced the collapse analysis of WTC 7. These areas included fire growth and spread, debris impact damage due to the collapse of WTC 1, transitioning from the structural fire response to the collapse analysis, and the analysis progression from initiation to global collapse.

3.4.2 Fires Simulated

The visual evidence indicated that the only fires of significant duration and intensity were on Floors 7 through 9 and 11 through 13.

- By 1:00 p.m., there was no visual evidence that the small, early fires on Floors 19, 22, 29, and 30 were still burning (NIST NCSTAR 1-9, Chapter 5). Therefore, these fires were not included in the four-step analysis sequence.

- There was no confirmed evidence of fires on other floors of WTC 7. The layout of the other tenant spaces (Floors 15 and above) indicated that, had there been fires of the duration and intensity of those on Floors 7 through 9 and 11 through 13, they would have been recorded in at least some of the photographic images or videos.

- There were no signs of fires on the 5th and 6th mechanical floors. There was little combustible material on the 6th floor, making a sustained and intense fire unlikely.

Hypothetically, there might have been fires on the 5th floor, since external views of the interior of these floors were inhibited by air intake and exhaust plenums, louvers, and/or transformer vault walls on the north, east and west faces (Figure 3–3 and Figure 3–4, reproduced from NIST NCSTAR 1-9, Chapter 3). Therefore, NIST performed simulations of the potentially severe pool fires that might have resulted from ignition of spillage (e.g., from a ruptured fuel supply line) of the diesel fuel present on the 5th floor or that might have been pumped to that floor. Four types of fires resulting from fuel line rupture in the northeast section of the 5th floor were analyzed (NIST NCSTAR 1-9, Chapter 9).

- An over-ventilated fire, in which the fuel burning could have been sustained for the approximately seven hours between the collapse of WTC 1 and the collapse of WTC 7. Result: The gas temperatures around all nine diesel generators would have quickly exceeded their operating limit, and there would have been no power to continue pumping fuel. Thus, the fire could not have been sustained.
- An over-ventilated fire, in which the burning rate was double that of the previous fire, representing a higher intensity fire of shorter duration. Result: The fire could not have been sustained for the same reason as in the previous case.
- An under-ventilated fire, in which the air handling system was turned off and the louvers were closed. The initial fuel burning rate was fit to the air availability. Result: The sustained air temperatures were not high enough to compromise the structure.

- An under-ventilated fire, in which the air handling system was turned off, but the louvers were open. Result: Smoke would have exhausted through the east louvers, and the imagery showed no such effluent.

An additional simulation was performed of an over-ventilated fire near the breach in the south wall. Result: The fire might have been able to damage the nearby columns, especially if their thermal insulation had been damaged by the debris from WTC 1. However, as will be seen later, the collapse of WTC 7 originated on the east side of the building, and there was no path for the hot gases to reach and weaken the structure on that side.

The diesel fuel in the day tank on Floor 5 was only equivalent to a few percent of the combustible furnishings on a tenant floor. It was unlikely that the tank would have been re-supplied because of multiple safeguards in the fuel delivery system.

NIST determined that a spray fire of the diesel fuel would have been less damaging than a pool fire, even though the spray fire temperature would have been a few hundred degrees higher. A fuel spray would have resulted from a small leak in the fuel supply piping, so the fuel escape rate would have been far less than in the over-ventilated pool fire scenarios. Had this small burning spray hit Column 79 directly, it would only have heated a small area of the column. NIST calculations (NIST NCSTAR 1-9, Chapter 4) showed that even if the entire column had been immersed in a 1400 °C flame, it would have taken 6 h to heat the column to the point of significant loss of strength and stiffness.

NIST also evaluated the possible contribution of diesel fuel from the day tanks on Floors 7, 8, and 9 to the fires on those floors. The amount of fuel available within the day tanks was insignificant compared to the mass of other combustibles on those floors. Nearly all the diesel fuel in the tanks that supplied the day tanks on the 8th and 9th floors was recovered months after the WTC 7 collapse. The diesel fuel could have contributed to the initial ignition and spread of the fires on the south side of Floor 7 and on the west side of Floors 8 and 9, but these fires would have been far removed from the critical structural systems on the east side of WTC 7.

Based on these analyses and review of the numerous interview transcripts[5], NIST concluded that it was highly unlikely that any fires on the 5th or 6th floors contributed significantly to the collapse of WTC 7.

NIST concluded that the only fires that could have led to structural weakening of WTC 7 were those on the 7th through 9th and 11th through 13th floors.

[5] For instance, sometime after 1:00 p.m., OEM and FDNY staff climbed the east stairway of WTC 7 and did not see much damage on the 4th, 5th, or 6th floors from their viewing location. They made no mention of fire, heat or smoke.

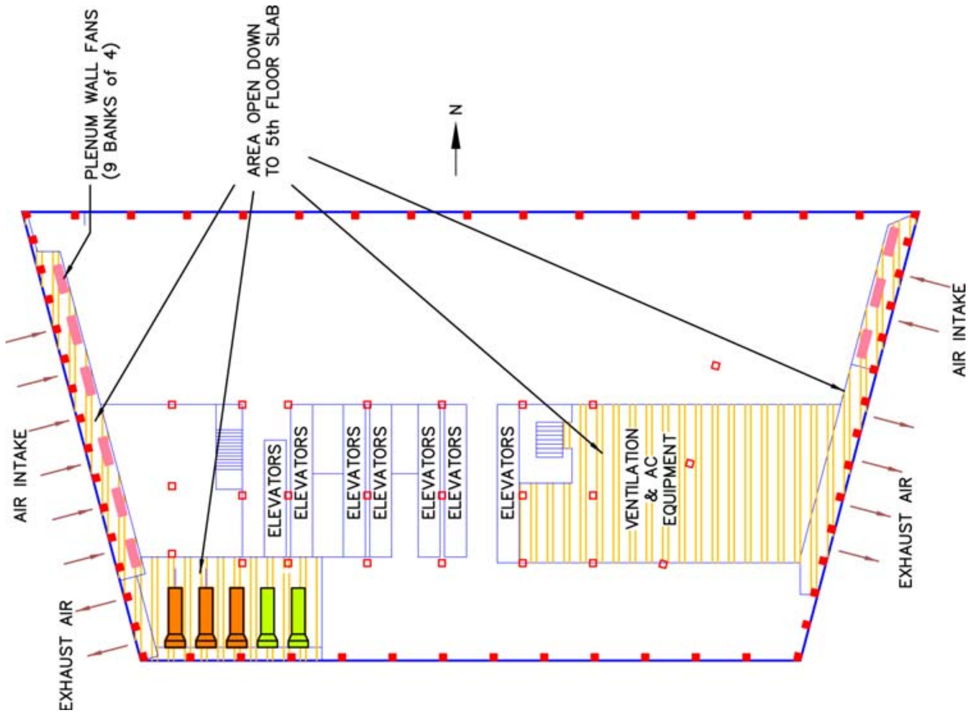


Figure 3–3. Layout of the 6th floor of WTC 7.

Based on architectural and mechanical drawings of WTC 7

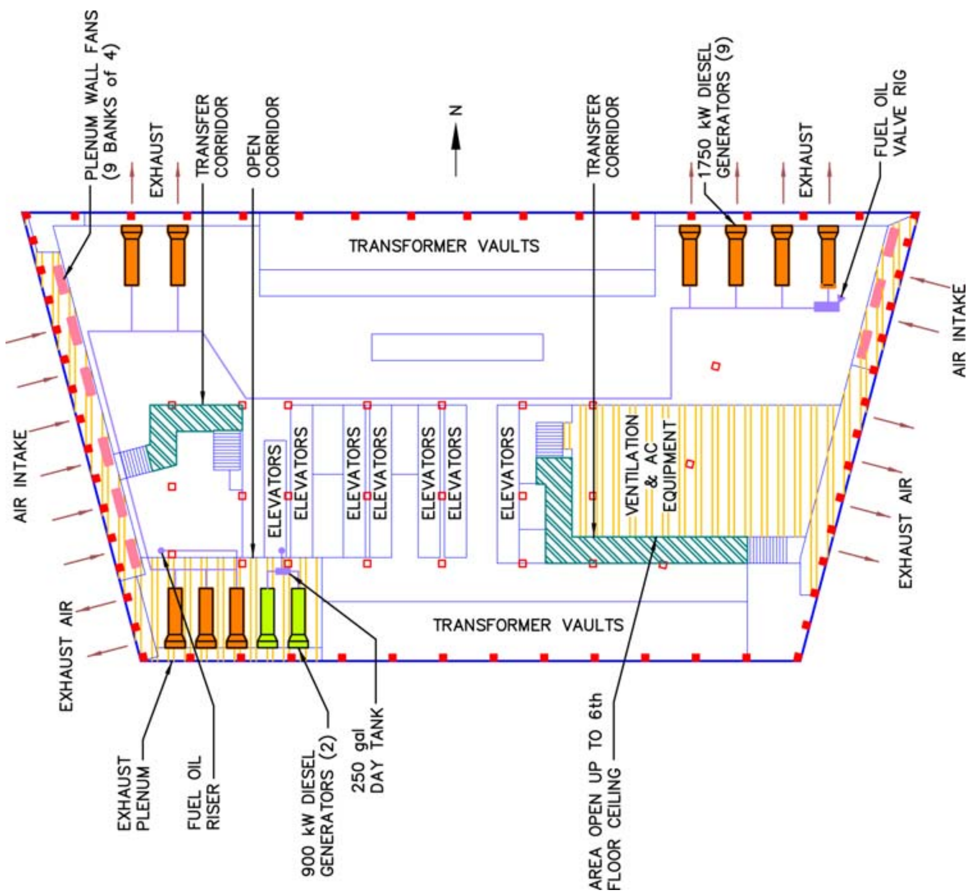


Figure 3–4. Schematic of the 5th floor of WTC 7 showing the locations of the emergency power system components.

Based on architectural and mechanical drawings of WTC 7

3.4.3 Fire Dynamics Simulator (FDS)

The major fires on Floors 7 through 9 and 11 though 13 in WTC 7 were simulated using the Fire Dynamics Simulator (FDS), version 4, in a manner similar to the simulations conducted for WTC 1 and WTC 2 (NIST NCSTAR 1-5F). There were far fewer photographs and videos of WTC 7 than of the towers; and, thus, the details of the WTC 7 fires were not as precise as for the fires in the towers. However, the imagery was sufficient to guide the WTC 7 fire simulations. Unlike the computations for WTC 1 and WTC 2, the fire simulations for WTC 7 were conducted for each floor individually, as there were no obvious pathways for the flames and heat to pass from one floor to another, aside from the debris-damaged area in the southwest corner of the building (NIST NCSTAR 1-9, Chapter 9). The fires on Floors 7, 8, and 12 were simulated using input from the visual imagery and established fire physics. The fire on Floor 9 was similar to that on Floor 8, and the simulation was derived from it. For the same reason, the fires on Floors 11 and 13 were derived from the fire on Floor 12. While use was made of the appearance of flames and window breakage in photographs and videos in formulating the simulations, the Investigation Team realized that the absolute timing of the simulations might not align exactly with the timing of the fires on September 11, 2001. A typical single floor fire simulation took up to two days on a Linux cluster with 8 processors.

Figure 3–5 shows hourly snapshots of the computed temperatures near the ceiling of the 8th floor. The general clockwise movement of the fires is in agreement with the visual images.

Figure 3–6 is a similar visualization of the temperatures resulting from the computed fires on the 12th floor. The general counterclockwise movement of the fires is evident.

3.4.4 Fire Structure Interface (FSI)

The Fire Structure Interface (FSI) was used to impose the gas temperatures from the FDS simulations on the structural components of WTC 7 to predict the evolving thermal state of the building (NIST NCSTAR 1-9, Chapter 10). The thermal analysis approach was similar to that used to simulate the fire induced thermal loads on WTC 1 and WTC 2 described in NCSTAR 1-5G. The FDS temperature data for use in the structural analysis were sampled at 30 min intervals. For each time step, a set of thermal data files was generated that specified the thermal state of the lower 16 stories of the building. Three different thermal response computations were used. Case A used the temperature data as obtained from the FDS simulation. Case B increased the Case A gas temperatures by 10 percent and Case C decreased the Case A gas temperatures by 10 percent. Given the limited visual evidence, the Investigation Team estimated, using engineering judgment, that a 10 percent change in temperatures was within the range of reasonable and realistic values for the fires in WTC 7 on September 11, 2001. The computational time for each Case was approximately one to two days on a single processor desktop computer.

Figure 3–7 shows the calculated heating of the structural steel on the lower 16 floors of WTC 7 for the Case B temperatures from the fire simulation. The floor slabs have been removed from the figure for clarity. Figure 3–8 is a typical rendition of the calculated heating of the top of a floor slab as a result of the Case B fire.

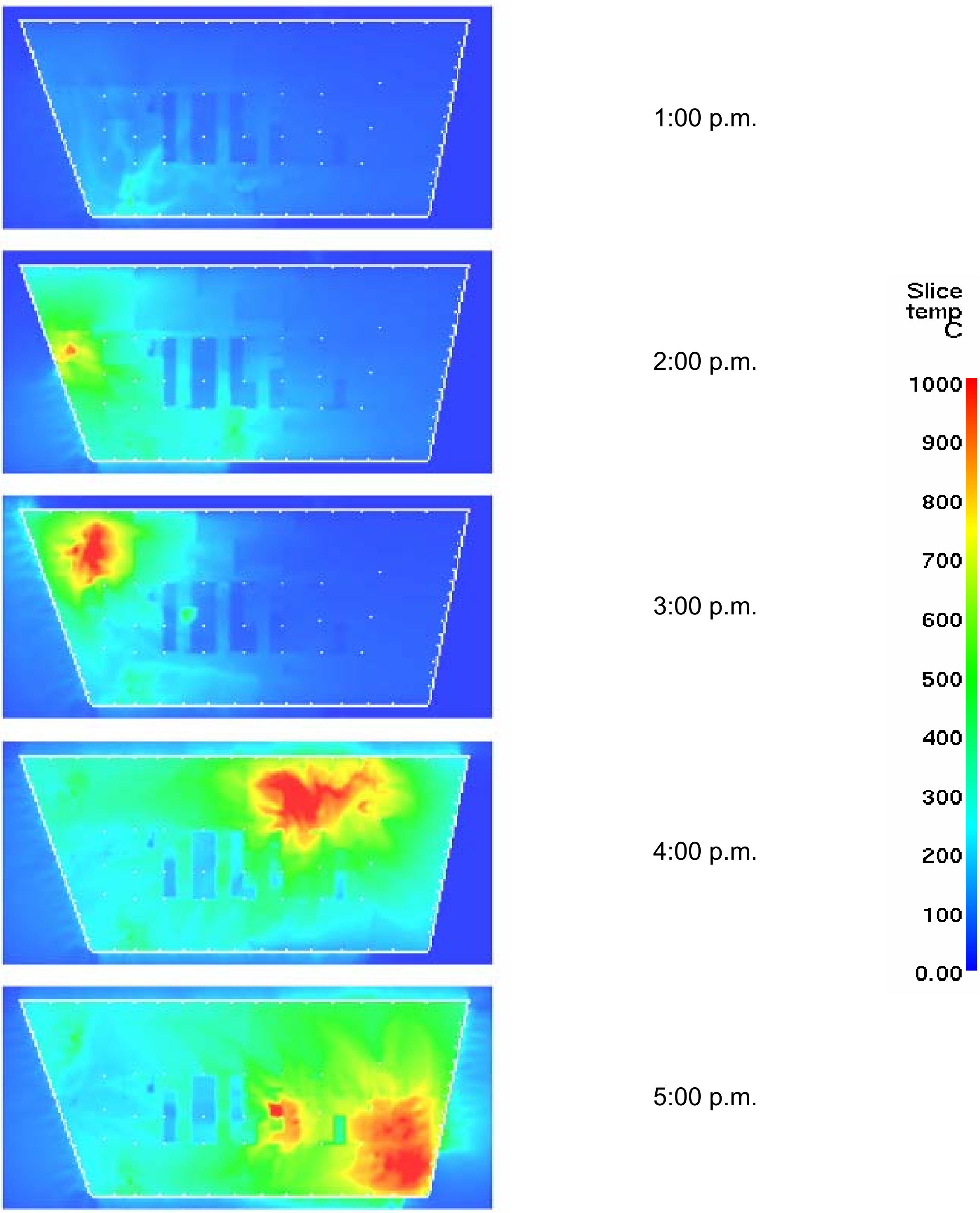


Figure 3–5. Progression of simulated fire on Floor 8 of WTC 7.

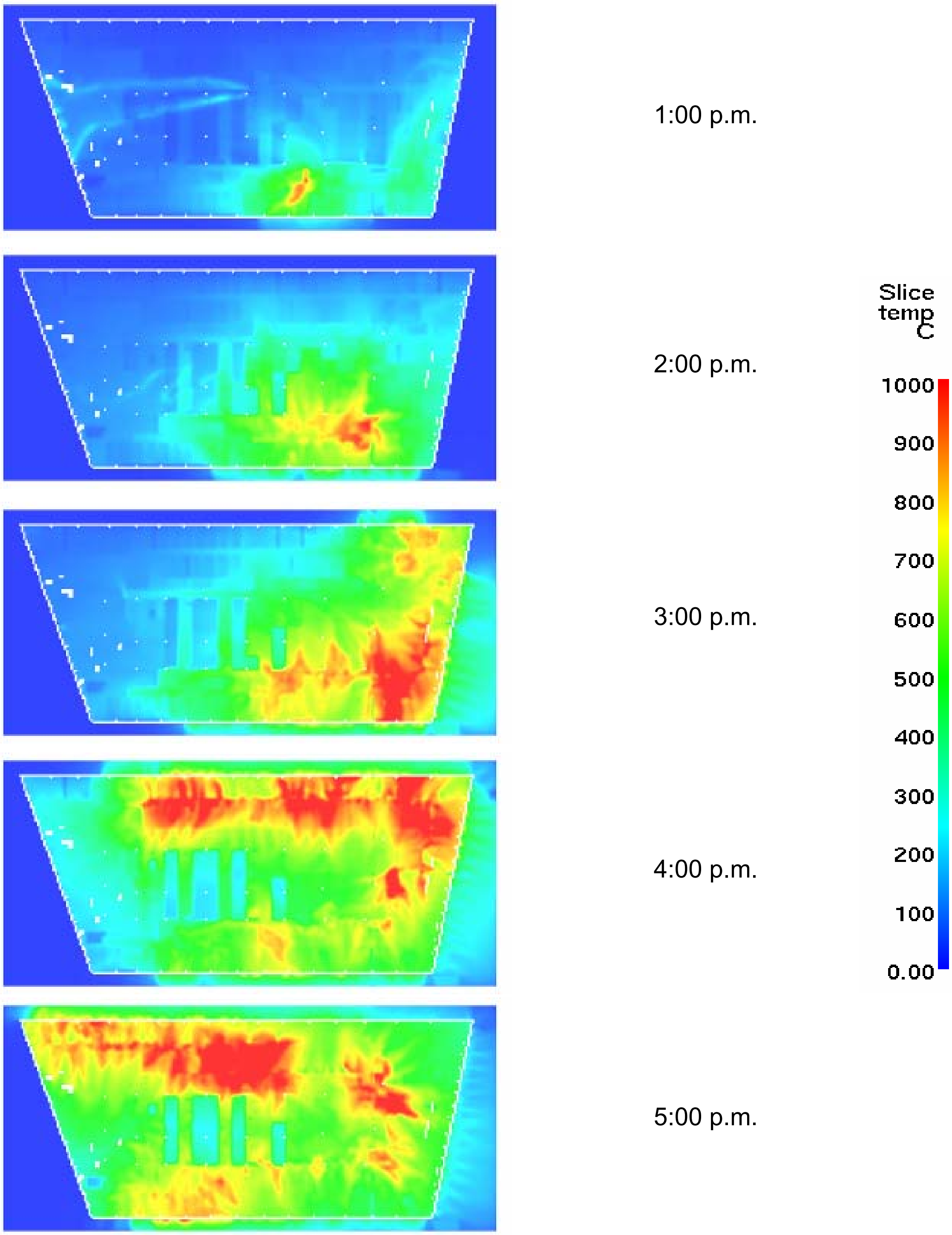


Figure 3–6. Progression of simulated fire on Floor 12 of WTC 7.

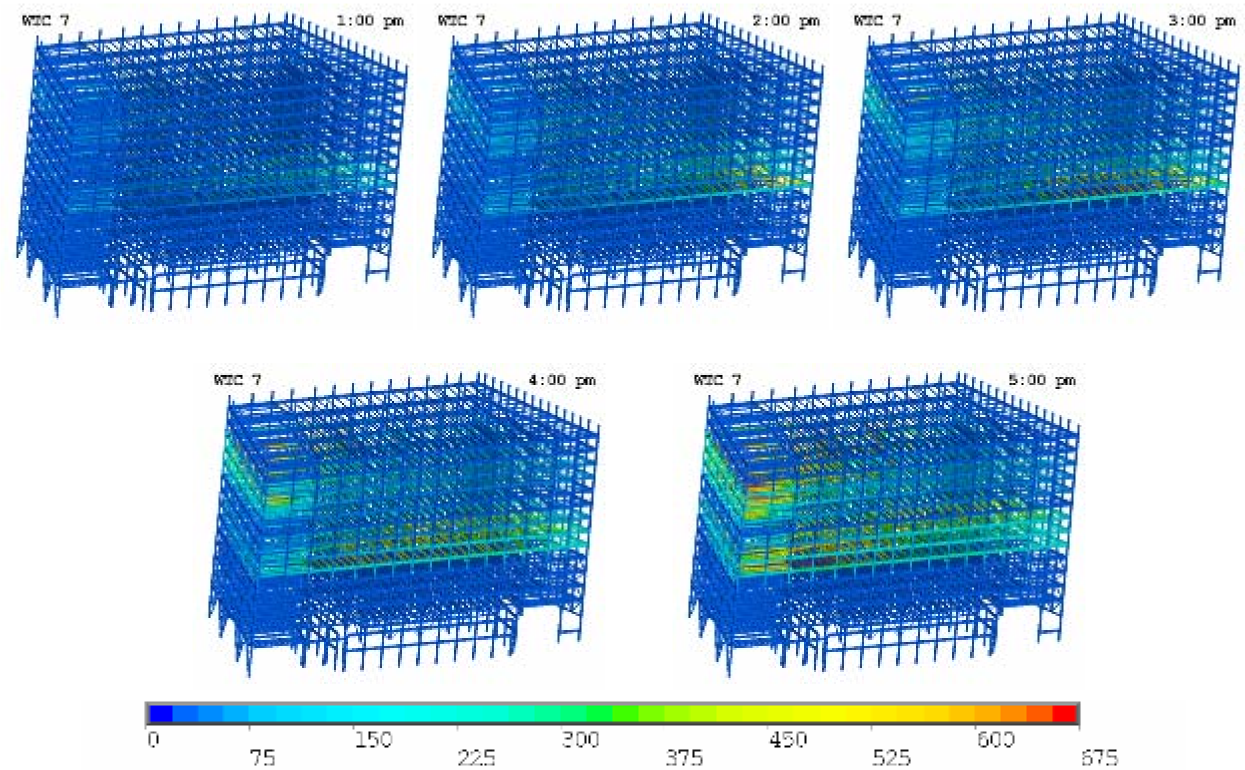


Figure 3–7. View from the northeast of the computed heating of the lower 16 floors of WTC 7 at five different instants in time.

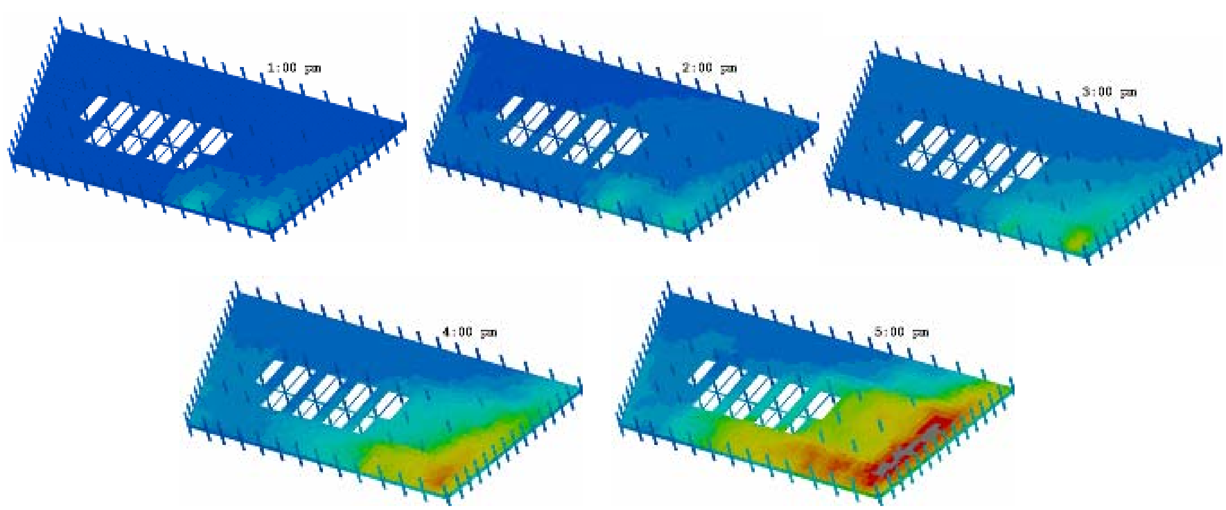


Figure 3–8. Computed temperature distribution (ºC) in the top layer of the concrete slab of Floor 12 at five different instants in time.

3.4.5 Structural Analysis of the Initial Failure Event using ANSYS

The structural response of the lower 16 stories of WTC 7 to the heating from the fires on Floors 7 through 9 and 11 through 13 was simulated using ANSYS, a finite element computational model that allowed including the temperature-varying properties of the structural materials. This analysis was used to determine the sequence of events that led to the collapse initiation (NIST NCSTAR 1-9, Chapter 11). In addition to the temperature-time histories from the FSI results, the structural model used temperature-dependent mechanical properties of the steels, welds, and bolts used in the construction of WTC 7, including elastic, plastic, and creep properties. The description of the building structure was based on architectural and structural drawings of the original building and subsequent building alterations.

Component structural analyses were conducted to identify critical behavior and failure mechanisms that could have contributed to the global structural response of the building. These component analyses included (1) buckling of a core column, (2) beam-to-girder connections under thermal loading, and (3) girder-to-column connections under thermal loading. Subsystem analyses were then performed that incorporated the behavior and failure mechanisms identified in the component studies. The subsystems analyses included (1) the northeast corner of a typical floor and (2) a full tenant floor, both under gravity and fire loads. Modifications were made to reduce the model size and complexity and to enhance computational performance, but without adversely affecting the accuracy of the results. Whenever modeling modifications were used, they were validated against the detailed component model results.

Due to the nonlinearities in the analysis, as well as fire-induced damage, a 30 min analysis could take a few weeks to complete. Due to the range of time steps that were required to reach equilibrium (e.g., from 10^{-6} seconds to 10s of seconds), a complete ANSYS analysis for a given thermal case took approximately six months to complete on a 64 bit workstation with quad-core, 3.0 gigahertz (GHz) processor, and 64 gigabyte (GB) of Random Access Memory (RAM). The use of user-defined elements prevented the use of parallel processing on a Linux cluster.

The three different thermal response cases (A, B, and C) were used in the ANSYS analysis. Based on the ANSYS model results, it became apparent that the calculated fire-induced damage to connections and beams were occurring at essentially the same locations and with similar failure mechanisms, but shifted in time. (Case C failures occurred at a later time than the same failures in Case A, and Case A failures occurred at a later time than Case B failures.) As a result, only the fire-induced damage produced by Case B temperatures was carried forward as the initial condition for the building collapse analysis, since the damage occurred in the least computational time (i.e., 6 months).

Figure 3-9 shows an example of the extent of structural damage from the fires, in this case for the 13th floor. At both 3.5 h and 4.0 h, connections, floor beams, and girders were damaged or had failed at steel temperatures that were approximately 400 °C or less, primarily due to the effects of thermal expansion. After 4.0 h of heating, there was substantially more damage and failures in the WTC 7 structural system than at 3.5 h of heating.

The ANSYS results were input to the LS-DYNA analysis when it appeared that an initial failure event might be imminent, and diagrams for the 16 floors modeled in ANSYS indicated some degree of uncertainty in selecting the time and damage state for the transition. However, it appeared likely the critical damage state occurred between 3.5 h and 4 h. Accordingly, as shown in the next section, LS-DYNA analyses were performed for both of these damage states.

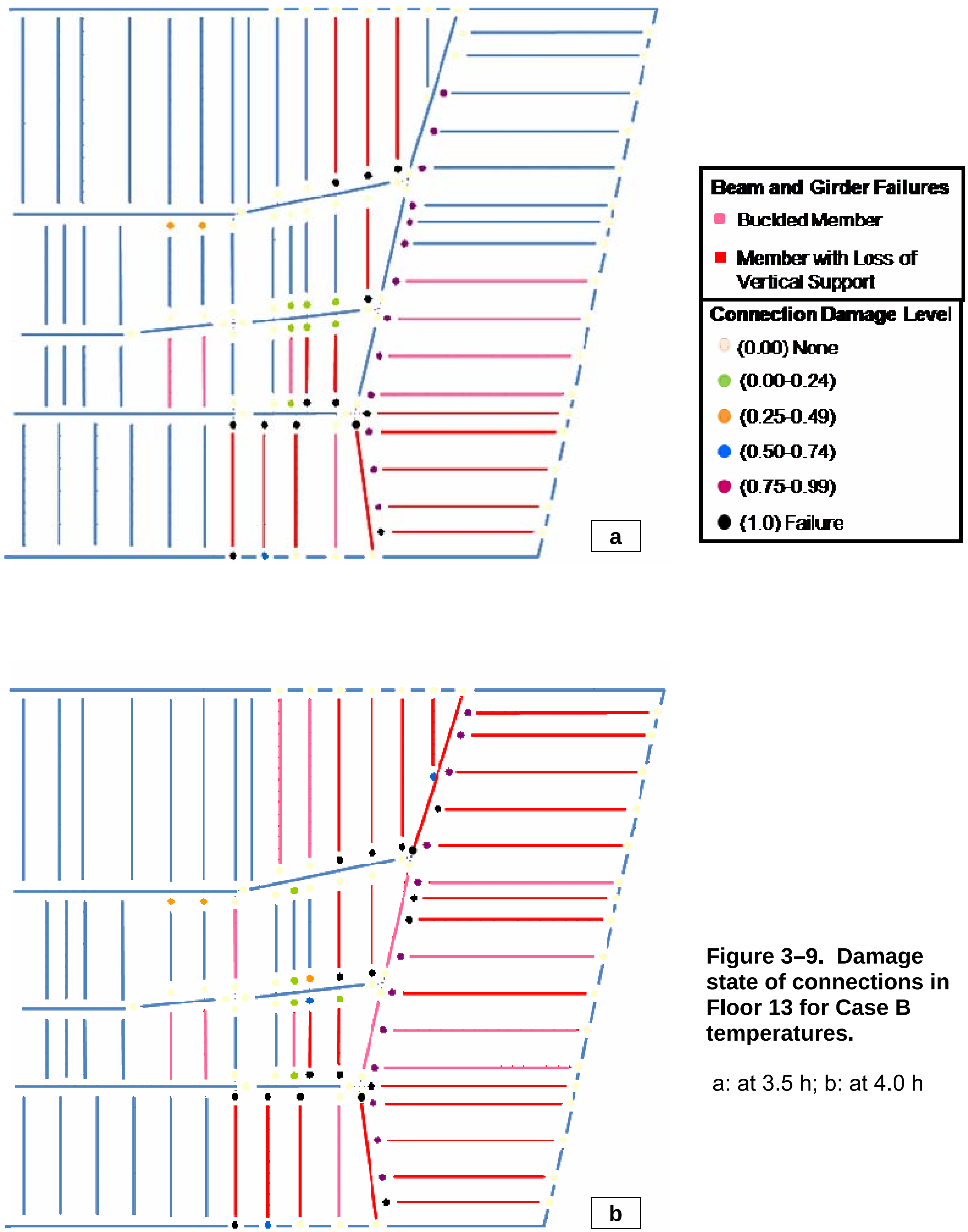


Figure 3–9. Damage state of connections in Floor 13 for Case B temperatures.

a: at 3.5 h; b: at 4.0 h

3.4.6 Global Collapse Analysis using LS-DYNA

A global finite element model of the WTC 7 building was developed in LS-DYNA to study its structural response to an initial failure event due to fire and to determine the sequence of events that led to collapse propagation and, ultimately, global collapse. LS-DYNA was capable of explicitly modeling failures, falling debris, and debris impact on other structural components. It could also model dynamic processes, including nonlinear material properties, nonlinear geometric deformations, material failures, contact between the collapsing structural components, and element erosion based on a defined failure criterion. In addition, LS-DYNA had capabilities to include thermal expansion and softening of materials. (For more detail, see NIST NCSTAR 1-9, Chapter 12, and NIST NCSTAR 1-9A.)

The description of the building structure was based on architectural and structural drawings of the original building and subsequent building alterations, as well as erection and shop fabrication drawings. Other input data required by the global LS-DYNA model were presented in the following sections of NIST NCSTAR 1-9::

- Extent of damage to the building by debris impact from the collapse of WTC 1 (Chapter 5).
- Photographic and videographic records with time stamps that documented the observed collapse sequence (Chapter 5).
- Temperature-dependent mechanical properties of steel (Appendix E) and concrete (NIST NCSTAR 1-6A) used in the construction of WTC 7.
- Fire-induced damage to floor beams, girders, and their connections from the 16 story ANSYS analysis (Chapter 11).
- Temperatures for structural components and connections, at the time the ANSYS analysis transferred data to the LS-DYNA analysis (Chapter 10).

Due to the nonlinearities in the analysis, as well as sequential local failures, a 25 s analysis took up to 8 weeks to complete. The analyses were run on a Linux cluster with a head node with two 64 bit, 2.4 GHz processors and 4 GB of RAM and compute node with two 64 bit, 2.6 GHz processors. Six of the compute nodes had 8 GB of RAM and the remaining two nodes had 16 GB RAM.

Three simulations were performed with the global LS-DYNA model.

- The first was based on NIST's best estimate of both the debris impact damage form WTC 1 and the fire-induced damage as developed using the ANSYS modeling. This occurred at 4 h in the ANSYS computation.
- The second simulation differed only in the input of a lesser degree of fire-induced damage, which occurred at 3.5 h in the ANSYS computation. The purpose of this LS-DYNA simulation was to determine whether a lesser degree of fire-induced damage could lead to the collapse of WTC 7.
- The third simulation was the same as the first, except that no debris impact damage was included. The purpose of this analysis was to determine the contribution of debris impact to the WTC 7

global collapse sequence and whether WTC 7 would have collapsed solely due to the effects of the fires.

The LS-DYNA model was initiated as follows to minimize any spurious dynamic effects associated with the loading sequence. First, gravity was applied slowly to the 47 floor structure, taking 4.5 s of elapsed simulation time.. Then, the debris impact damage from the collapse of WTC 1 was applied to the structure instantaneously by removing from the model the damaged elements that were no longer capable of bearing their loads. The structure was then allowed to damp residual vibrations for 2 s. Over the next 2 s, the structural temperatures were ramped up to the levels from the ANSYS simulation . Fourth, the fire-induced damage obtained from the 16 story ANSYS analysis, including damage to floor beams, girders, and connections, was applied instantaneously. The damage was from the computation of Case B at 4 h after the initiation of the fires in FDS. The heated, damaged structure was then free to react. The time at which the east penthouse began to descend was defined as 0.0 s, i.e., the beginning of the collapse of WTC 7.

The global analysis with fire-induced damage at 4.0 h most closely matched the observed collapse events, and the following discussion begins with the results from this analysis.

Figure 3–10 through Figure 3-14 depict the state of the WTC 7 structure at various times as the structure collapsed. The first four figures are views of the lowest 18 floors of the WTC 7 building core from the south. In these graphics, the exterior columns and some of the tenant floor structure spanning between the core and the exterior have been removed for an unobstructed view of the core. The scale on the right side shows the absolute (i.e., without any indication of direction) lateral displacement of each structural element. Displacements greater than 0.15 m (6 in.) are also shown in red.

Figure 3–10 shows the beginning of upper floor failures on the east side of the building at 0.5 s, following the buckling of Columns 79, 80, and 81. The east penthouse, which was supported by these three columns, had just begun to descend. About 2 s later, as shown in Figure 3–11, the collapse of all the east sections of all the floors had occurred, the upper floors had moved southward, Truss 2 had been damaged, and the westward progression of the building failure was underway. Figure 3–12 and Figure 3–13, only 2 s apart, indicate the speed with which the westward column failures proceeded between Floors 7 and 14.

In Figure 3-14, the total collapse of the building is underway. The two views cover the lower half of the building. The purple area at the bottom is the Con Edison substation. With no fires on the west side of Floors 10 through 14, the intact floor framing pulled the exterior columns inward as the interior columns fell downward. Loads from the buckled interior columns were redistributed to the exterior columns, which, in turn, buckled the exterior columns between Floors 7 and 14 within approximately 2 s. At that point, the entire building above the buckled-column region moved downward as a single unit, resulting in the global collapse of WTC 7.

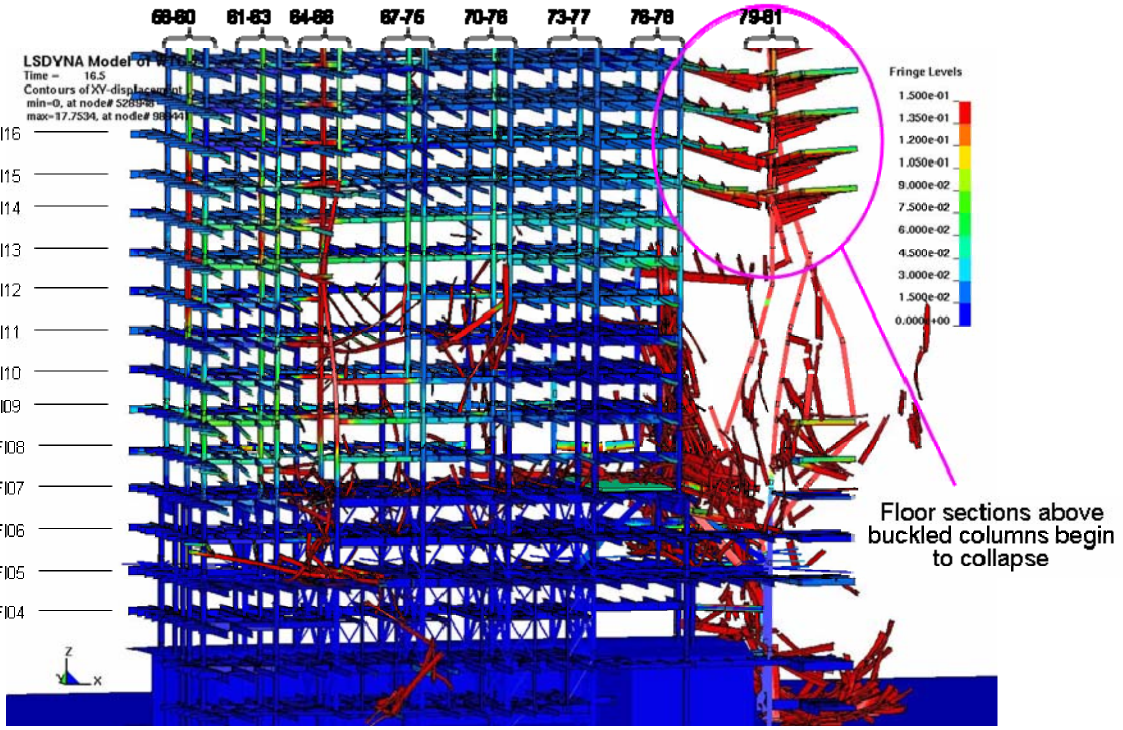


Figure 3–10. Vertical progression of failures on the east side of the building at 0.5 s following the initiation of the collapse.

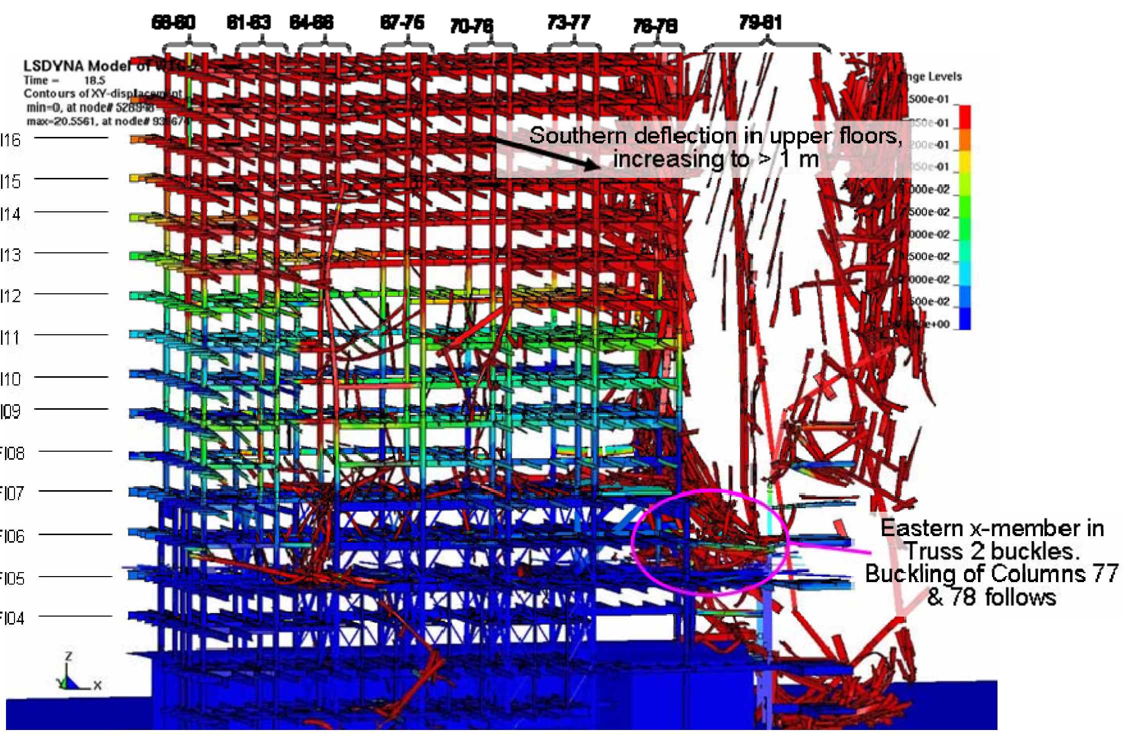


Figure 3–11. Failure of Columns 77 and 78 due to failure of Truss 2 fails from debris impact at 2.5 s following the initiation of the collapse.

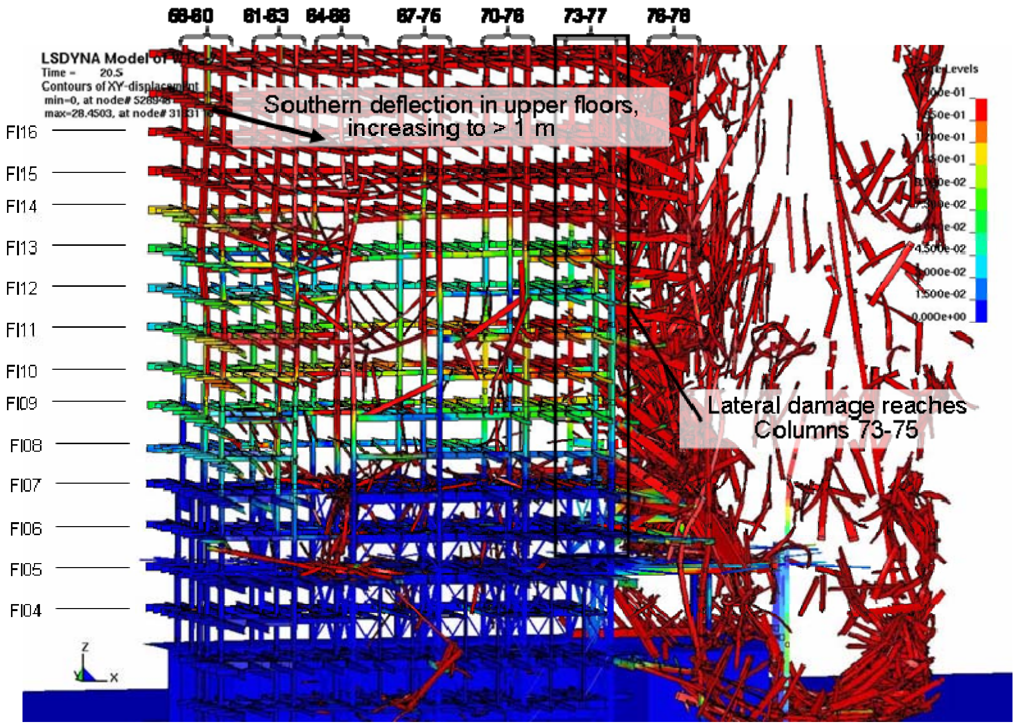


Figure 3–12. Failure of Columns 73 to 75 from the load redistribution and debris impact at 4.5 s following the initiation of the collapse.

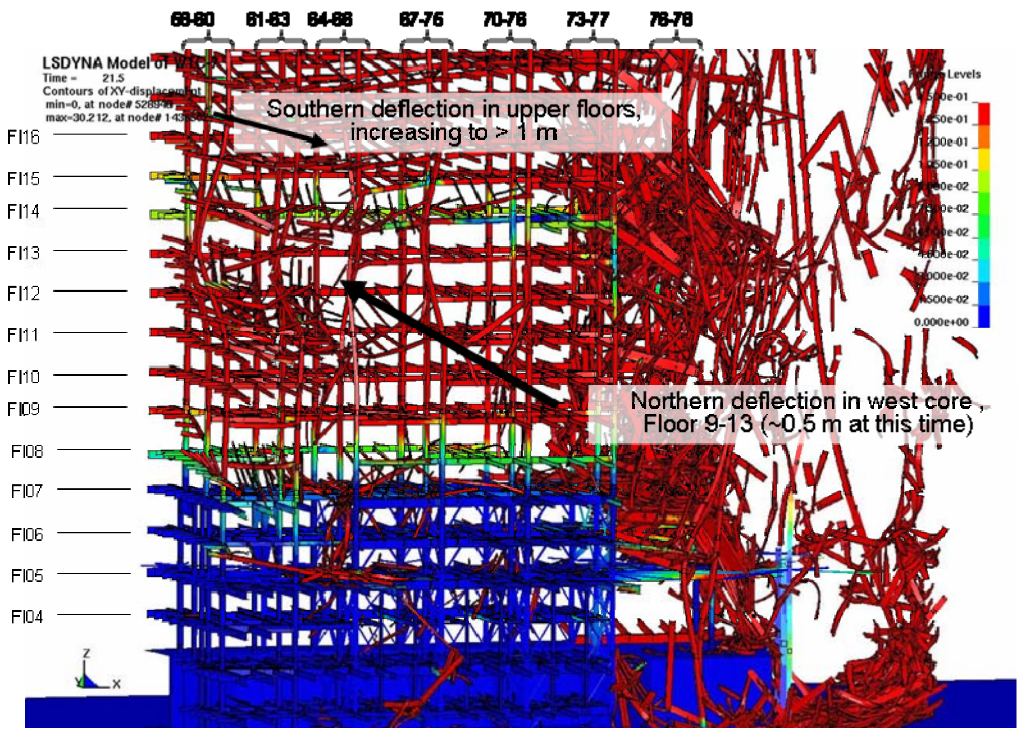


Figure 3–13. Buckling of all interior columns at 6.5 s following the initiation of the collapse.

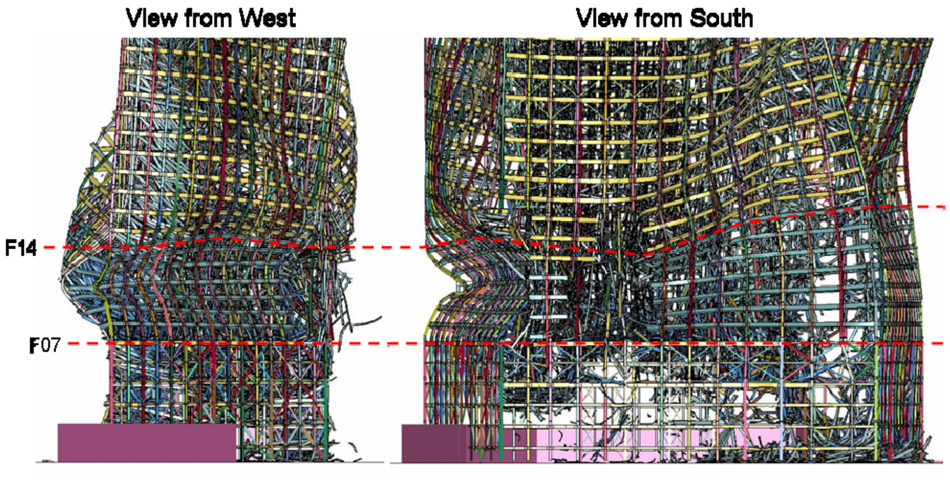


Figure 3-14. Buckling of the lower exterior columns within 1 s of Figure 3–13.

The second LS-DYNA analysis (lesser degree of fire-induced damage) did not lead to a collapse-initiating event, despite the extensive damage shown in Figure 3–9a.

The third LS-DYNA analysis demonstrated that the fire-induced damage led to the collapse of WTC 7, even without any structural damage from the debris impact. However, the mechanism of the collapse differed from the first analysis. This is discussed further in the next section.

3.5 ACCURACY OF THE PROBABLE COLLAPSE SEQUENCE

Independent assessment of the validity of the key steps in the collapse of WTC 7 was a challenging task. Some of the photographic information had been used to direct the simulations. For example, the timing of the appearance of broken windows was an input to the fire growth modeling. However, there were significant observables that were usable as corroborating evidence, as shown in Table 3–1. The "Observation Times" were determined from examinations of photographs and videos shot on September 11, 2001. The times in the second and third columns are from the two global analyses with and without debris impact damage for Case B temperatures at 4.0 h.

3.5.1 Aspects prior to the Global Collapse

Analysis of a video shot prior to and during the collapse showed an east-west vibration of the building prior to its collapse (NIST NCSTAR 1-9, Chapter 5 and Appendix C). The horizontal motion (± 2 in.) began 6 s before the east penthouse began to move downward. The horizontal building motion started at nearly the same time as the cascading floor failures started in the LS-DYNA analysis (-6.5 s), which preceded the buckling failure of Column 79. A seismic signal approximately 10 s prior to the onset of collapse was likely due to the falling of debris from the collapse. It is consistent that the falling debris (on the east side of the building) imparted some momentum in the east west direction as it descended.

The two calculated times and the observed time for the descent of the east penthouse below the roofline were quite similar, independent of the debris impact damage. At this point, the two computations were also similar to each other in the manner in which the vertical progression of the collapse was proceeding.

Table 3–1. Comparison of global structural model predictions and observations for WTC 7, Case B.

Observation Time (s)	Analysis Time (s) with Debris Impact Damage	Analysis Time (s) without Debris Impact Damage	Event
≈ -6 s [a]	-6.6 s	-6.6 s	Start of cascading failure of floors surrounding Column 79
N/A [b]	-1.3	-1.4	Buckling of Column 79, quickly followed by buckling of Columns 80 and 81
≡ 0	≡ 0	≡ 0	Start of descent of east penthouse
2.0	2.4, 2.7	2.3, 2.6	Descent of east penthouse below roofline (First value: observed from the northwest and below; second value: observed from the north at the roofline)
N/A[b]	3.5-6.1	3.2-13.5	Buckling of columns across core, starting with Column 76
6.9	6.3	9.8	Initial downward motion of the north face roofline at the eastern section of the building
8.5	7.3, 7.7	8.7, 9.2	Descent of the east end of the screenwall below the roofline (First value: observed from the northwest and below, second value: observed from the north at the roofline)
9.3	6.9, 7.3	10.6, 10.9	Descent of the west penthouse below the roofline (First value: observed from the northwest and below, second value: observed from the north at the roofline)

a: From NIST NCSTAR 1-9, Appendix C and Chapter 8.

b: Not available

The horizontal progression of buckling core columns was interior to the building and could not have been observed from the street. The process occurred over a longer duration of 10.3 s (13.5 s minus 3.2 s) for the analysis without debris impact damage than for the duration of 2.6 s (6.1 s minus 3.5 s) for the analysis with impact damage. In the analysis without debris impact damage, the lack of core framing damage on the lower west side resulted in a sequence of interior column failures from east to west that occurred at a more uniform rate. In the analysis with debris impact damage, the core framing damage on the west side resulted in a more rapid failure of the west interior columns in the last stages of the horizontal progression.

The initial downward movement of the north face from the northeast corner to the east side of the screenwall was observed at 6.9 s after the initial downward motion of the east penthouse. The LS-DYNA analyses with and without impact damage straddled that value.

3.5.2 Aspects following the Collapse Initiation

Once simulation of the global collapse of WTC 7 was underway, there was a great increase in the uncertainty in the progression of the collapse sequence, due to the random nature of the interaction, break up, disintegration, and falling of the debris. The uncertainties deriving from these random processes increasingly influenced the deterministic physics-based collapse process, and the details of the progression of the horizontal failure and final global collapse were increasingly less precise.

Thus, while the two predictions of the time of descent of the west penthouse also straddled the observed time, the mechanisms of building collapse were quite different. In the analysis without debris impact damage, the exterior columns buckled near mid-height of the building, approximately between Floors 17 and 29. In the analysis with debris impact damage, the exterior columns buckled between Floors 7 to 14, due to the influence of the exterior damage near the southwest corner. In both analyses, the eastern exterior wall deflected inward at the roof level as the structure became unsupported after the vertical collapse event. The western wall also deflected inward in the analysis without debris impact damage, as it was pulled inward as the last line of core columns failed.

There was another observable feature that occurred after the global collapse was underway and no science-based simulation capability exists to capture it. After the exterior facade began to fall downward at 6.9 s, the north face developed a line or “kink” near the end of the core at Column 76. As shown in Figure 5-205, the northeast corner then began to displace to the north at about 8.8 s, and the kink was visible at 9.3 s. The kink and rotation of the northeast façade occurred 2 s to 3 s after the exterior façade had begun to move downward, as a result of the global collapse. The simulations do show the formation of the kink, but any subsequent movement of the building is beyond the reliability of the physics in the model.

3.5.3 Accuracy Appraisal

Given the complexity of the modeled behavior, the global collapse analyses matched the observed behavior reasonably well. The close similarity of the timing and the nature of the events up to the initiation of global collapse is strong confirmation of the extent and nature of the structural failures in the interior of the building and the accuracy of the four-step simulation process. The overall simulation of the collapsing building with damage better matched the video observations of the global collapse. The global collapse analysis confirmed the leading collapse hypothesis, which was based on the available evidence.

3.6 COLLAPSE TIME

NIST was interested in estimating how closely the time for WTC 7 took to fall compared with the descent time if the building were falling freely under the force of gravity (NIST NCSTAR 1-9, Chapter 12). Assuming that the descent speed was approximately constant, the two quantities needed for the determinations were (1) a length that some feature of the building descended and (2) the time it took to fall that distance. The chosen feature was the top of the parapet wall on the roofline of the north face. The length was the difference between the position of the roofline prior to the collapse and the last position the roofline could be observed before it was obstructed by a building in the foreground.

The elevation of the top of the parapet wall was +925 ft 4 in. The lowest point on the north face of WTC 7 visible on the Camera 3 video (Section 5.7.1) prior to any downward movement was the top of the windows on Floor 29, which had an approximate elevation of +683 ft 6 in. Thus, the distance that the roofline moved downward before it disappeared from view was 242 ft. The relative time at which the roofline began to descend was 20.60 s, and the relative time when the roofline dropped from view behind the buildings was 25.97 s. The time the roofline took to fall 18 stories was 5.4 s, with an uncertainty of no more than 0.1 s.

The theoretical time for free fall (i.e., neglecting air friction), was computed from,

$$t = \sqrt{\frac{2h}{g}} \quad ,$$

where t is the descent time (s), h is the distance fallen (ft), and g is the gravitational acceleration constant, 32.2 ft/s^2 (9.81 m/s^2). Upon substitution of h = 242 ft. in the above equation, the estimated free fall time for the top of the north face to fall 18 stories was approximately 3.9 s. The uncertainty in this value was also less than 0.1 s.

Thus, the actual time for the upper 18 stories to collapse, based on video evidence, was approximately 40 percent longer than the computed free fall time and was consistent with physical principles.

This page intentionally left blank.

Chapter 4
PRINCIPAL FINDINGS

4.1 INTRODUCTION

This chapter presents the findings of the NIST Technical Investigation, organized according to the first three of the four Investigation objectives for Building 7 of the New York World Trade Center (WTC). The fourth objective ("Identify areas in current building and fire codes, standards, and practices that warrant revision") is the subject of Chapter 5 of this report. The findings were derived from the extensive documentation summarized in the preceding chapters and described in detail in the accompanying reports. While NIST was not able to compile a complete documentation of the history of WTC 7, due to the loss of records over time and due to the collapses, the investigators were able to acquire information adequate to arrive at and firmly support the findings and recommendations compiled in this chapter and the next. The chapter begins with summary statements and continues with the listing of the full set of principal findings.

4.2 SUMMARY

Objective 1: Determine why and how WTC 7 collapsed.

- WTC 7 withstood debris impact damage that resulted in seven exterior columns being severed and subsequently withstood conventional fires on several floors for almost seven hours.

- The collapse of WTC 7 represents the first known instance of the total collapse of a tall building primarily due to fires. The collapse could not have been prevented without controlling the fires before most of the combustible building contents were consumed.

- WTC 7 collapsed due to uncontrolled fires with characteristics similar to previous fires in tall buildings. The fires in WTC 7 were similar to those that have occurred previously in several tall buildings (One New York Plaza, 1970, First Interstate Bank, 1988, and One Meridian Plaza, 1991) where the automatic sprinklers did not function or were not present. However, because of differences between their structural designs and that of WTC 7, these three buildings did not collapse. Fires for the range of combustible contents in WTC 7 (4.0 lb/ft^2 on Floors 7 to 9 and 6.4 lb/ft^2 on Floors 11 to 13) persisted in any given location for approximately 20 minutes to 30 minutes. Had a water supply for the automatic sprinkler system been available and had the sprinkler system operated as designed, it is likely that fires in WTC 7 would have been controlled and the collapse prevented.

- The probable collapse sequence that caused the global collapse of WTC 7 was initiated by the buckling of Column 79, which was unsupported over nine stories, after local fire-induced damage led to a cascade of floor failures. The buckling of Column 79 led to a vertical progression of floor failures up to the east penthouse and to the buckling of Columns 80 and 81. An east-to-west horizontal progression of interior column buckling followed, due to loss of lateral support to

adjacent columns, forces exerted by falling debris, and load redistribution from other buckled columns. The exterior columns then buckled as the failed building core moved downward, redistributing its loads to the exterior columns. Global collapse occurred as the entire building above the buckled region moved downward as a single unit.

- The collapse of WTC 7 was a progressive collapse. The American Society of Civil Engineers defines progressive collapse—also known as disproportionate collapse—as the spread of local damage, from an initiating event, from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it (ASCE 7-05). Despite extensive thermal weakening of connections and buckled floor beams, fire-induced damage in the floor framing surrounding Column 79 over nine stories was the determining factor causing the buckling of Column 79 and, thereby, initiating progressive collapse. This is the first known instance where fire-induced local damage (i.e., buckling failure of Column 79; one of 82 columns in WTC 7) led to the collapse of an entire tall building.

- The transfer elements (trusses, girders, and cantilever overhangs) did not play a significant role in the collapse of WTC 7. Neither did the Con Edison substation play a significant role in the collapse of WTC 7.

- Prior to the collapse, there had been no damage to the SFRM that was applied to the steel columns, girders, and beams, except in the vicinity of the structural damage from the collapse of WTC 1, which was near the west side of the south face of the building.

- Even without the initial structural damage caused by debris impact from the collapse of WTC 1, WTC 7 would have collapsed from fires having the same characteristics as those experienced on September 11, 2001.

- Early fires in the southwest region of the building did not play a role in the collapse of WTC 7. The fires in this region were not severe enough to heat the structure significantly; and, unlike the northeast region, where collapse initiated, there were no columns supporting long span floors in the southwest region.

- The collapse time of the upper 18 stories of the north face of WTC 7 (the floors clearly visible in the video evidence) was 40 percent greater than the computed free fall time. This is consistent with physical principles.

- Diesel fuel fires did not play a role in the collapse of WTC 7. The worst-case scenarios associated with fires being fed by the ruptured fuel lines (a) could not have been sustained long enough, or could not have generated sufficient heat, to raise the temperature of a critical column (i.e., Column 79) to the point of significant loss of strength or stiffness, or (b) would have produced large amounts of visible smoke that would have emanated from the exhaust louvers. No such smoke discharge was observed.

- Hypothetical blast events did not play a role in the collapse of WTC 7. Based on visual and audio evidence and the use of specialized computer modeling, NIST concluded that blast events did not occur, and found no evidence whose explanation required invocation of a blast event. Blast from

the smallest charge capable of failing a critical column (i.e., Column 79) would have resulted in a sound level of 130 dB to 140 dB at a distance of at least half a mile if unobstructed by surrounding buildings (such as along Greenwich Street or West Broadway). This sound level is consistent with standing next to a jet plane engine and more than 10 times louder than being in front of the speakers at a rock concert. There were no witness reports of such a loud noise, nor was such a noise heard on the audio tracks of video recordings of the WTC 7 collapse.

Objective 2: Determine why the injuries and fatalities were so high or low depending on location, including all technical aspects of fire protection, occupant behavior, evacuation, and emergency response.

- There were no serious injuries or fatalities because the estimated 4,000 occupants of WTC 7 reacted to the airplane impacts on the two WTC towers and began evacuating before there was significant damage to WTC 7. Evacuation of the building took just over an hour.

- The occupants were able to use both the elevators and the stairs, which were as yet not damaged, obstructed, or smoke-filled.

- Building management personnel held the occupants in the building lobby until they identified an exit path that was safe from the debris falling from WTC 1 across the street.

- The decision not to continue evaluating and fighting the fires was made hours before the building collapsed, so no emergency responders were in or near the building when the collapse occurred.

Objective 3: Determine what procedures and practices were used in the design, construction, operation, and maintenance of WTC 7.

- The design of WTC 7 was generally consistent with the NYCBC.

- Consistent with the NYCBC, there was no redundancy in the source of water supply for the sprinkler system in the lower 20 floors of WTC 7. Since there was no gravity-fed overhead tank supplying these floors, the sprinkler system could not function when the only source of water, which was from the street mains, was not available.

- Current practice for the fire resistance design of structures, based on the use of ASTM E 119 standard test method, is deficient since the method was not designed to include key fire effects that are critical to structural safety. Specifically, current practice does not capture: (a) important thermally-induced interactions between structural subsystems, elements, and connections—especially restraint conditions; (b) system-level interactions—especially those due to thermal expansion—since columns, girders, and floor subassemblies are tested separately; (c) the performance of connections under both gravity and thermal effects; and (d) scale effects in buildings with long span floor systems.

- Current practice also does not require design professionals to possess the qualifications necessary to ensure adequate passive fire resistance of the structural system. In current practice, architects typically rely on catalogued ASTM E 119 test data to specify the required passive fire protection that is needed for the structure to comply with the building code. They are not required to

explicitly evaluate the fire performance of the structure as a system (such as analyzing the effect of the thermal expansion or sagging of floor beams on girders, connections, and/or columns). Structural engineers are not required to consider fire as a load condition in structural design. Fire protection engineers may or may not be called upon to assist the architect in specifying the required passive fire protection. Thus, none of these professionals has been assigned the responsibility to ensure the adequate fire performance of the structural system.

- There is a critical gap in knowledge about how structures perform in real fires, particularly considering: the effects of the fire on the entire structural system; the interactions between the subsystems, elements, and connections; and scaling of fire test results to full-scale structures (especially for structures with long span floor systems).

4.3 THE MECHANISMS OF BUILDING COLLAPSE

4.3.1 Debris Impact Damage from the Collapse of WTC 1

- WTC 7 was damaged by debris from the collapse of WTC 1, which occurred at 10:28:22 a.m. However, WTC 7 collapsed at 5:20:52 p.m., nearly seven hours later.

- The structural damage to WTC 7 was primarily located at the southwest corner and adjacent areas of the west and south faces, on Floors 5 through 17. Severed columns were located between Floors 7 and 17 on the south face (six columns) and the west face (one column) near the southwest corner. Cladding damage extended over much of the south face, and ranged from broken windows to removal of granite panels and windows.

4.3.2 Reconstruction of the Fires

- There were fewer photographs and videos of the WTC 7 fires than there were of the fires in the WTC towers. This resulted in intermittent coverage of the building exterior from about 11:00 a.m. until just after the collapse at 5:20:52 p.m. Nonetheless, the visual evidence was sufficient to guide the reconstruction of the growth patterns of the fires.

- Fires were observed on multiple floors of WTC 7 following the collapse of WTC 1. The fires were likely to have started at locations facing WTC 1, caused by flaming debris, induced electrical failures, etc.

  - Early fires were seen on the southwest corner of Floors 19, 22, 29, and 30 shortly after noon. These were short-lived. Firefighters reported seeing fires on the south and west faces of WTC 7 as soon as visibility allowed (estimated to be 11:00 a.m. to 12:00 p.m.).

  - Sustained fires occurred on Floors 7, 8, 9, 11, 12, and 13. The fires on these six floors were fed by combustibles (e.g., desks, chairs, papers, carpet) that were ordinary for commercial occupancies.

- Unlike the situation in the WTC towers, there was no widespread spraying of jet fuel to ignite numerous workstations simultaneously. Rather, in the earlier hours of the fires, the flames would have spread from one workstation to another, which is a much slower process.

- On each floor, ignition was likely of a single workstation component or office furnishing item; growth over the full cluster of workstations or office took several minutes.

  - On Floors 7 through 9 (open landscaping), the initial fire spread was likely by flame contact with an adjacent workstation and then radiative ignition of a workstation cluster across an aisle. By the time this second cluster was fully involved, the prior cluster would have burned out. Eventually the upper gas layer over enough of the huge open space would likely be hot enough for radiatively enhanced ignition of multiple workstations, i.e., non-linear growth.

  - On Floors 11 through 13 (enclosed offices), the fire would likely have grown within an office, reaching flashover in several minutes. After about 15 minutes, the ceiling tile system would likely fail and the hot gases would create a local hot upper layer. Thermal radiation from this layer would have ignited adjacent offices. Offices across a corridor would likely have ignited more slowly.

- The collapse of WTC 7 was not caused by diesel fuel fires or by fire-induced failure of the transfer trusses on Floors 5 and 6.

  - Simulation of hypothetical, worst-case fire scenarios on these floors showed that pool fires, associated with ruptured diesel fuel lines, (a) would have raised the temperatures near the generators to the point where they all would have failed, cutting off the electrical power to the fuel pumps, (b) could not be sustained long enough, or generated too little heat, to raise the temperatures of the steel and concrete structure to the point of significant loss of strength or stiffness, and/or (c) would have exhausted smoke from the exhaust louvers, which was not observed.

  - A diesel fuel spray fire on Floor 5 would have been less damaging than a pool fire. To be a spray, the fuel escape rate would have been too small to heat Column 79, even if it hit it directly.

  - The day tanks on Floors 7, 8, and 9 contained diesel fuel equivalent to only a few percent of the office combustibles on those floors. Safeguards in the fuel delivery system would have prevented the tanks being re-supplied. The supply tanks for the day tanks on Floors 8 and 9 were found to be nearly full several months after the collapse of WTC 7. The heat from a day tank fire on Floor 7 would not have reached the transfer trusses or Column 79.

  - The absence of diesel fuel fires on Floor 5 was consistent with the information from interviews that sometime after 1:00 p.m., OEM and FDNY staff climbed the east stairway of WTC 7 and did not see much damage on Floors 4, 5, or 6 from their viewing location. They made no mention of fire, heat or smoke.

  - The transfer trusses and a girder were isolated from the diesel fuel lines and the generators by masonry walls. No mechanism for indirect heating of Transfer Trusses 1 or 2 was found.

- There was no evidence that the fires spread from floor to floor, except, perhaps, just prior to the collapse of the building.

- The fires on Floors 7 through 9 generally spread clockwise from the southwest corner of the floor. The fires on Floors 11 through 13 generally spread counterclockwise. All the fires were burning in the northeast region at around mid-afternoon.

- Simulations of the fires using the Fire Dynamics Simulator (FDS) generated air temperatures comparable to those in large-room fire tests of office workstations. Compared to the actual fires, the simulated fires followed the same general paths. The simulations of the Floor 12 fires (and thus the derivative Floor 11 and 13 fires) may have overestimated the duration of the fires and the fraction of the burning near the north face windows, relative to the fraction of burning in the interior of the tenant space.

- Doubling the estimated combustible fuel load on the open-landscaped Floor 8 from 20 kg/m^2 (4 lb/ft^2) to 40 kg/m^2 (8 lb/ft^2) led to a predicted fire spread rate that was slower than actually observed. Decreasing the combustible fuel load on the highly partitioned Floor 12 from 32 kg/m^2 (6.4 lb/ft^2) to the estimated load on Floor 8 had no significant effect on the fire spread rate. This indicated that the overestimation of burning duration was less likely due to overestimation of the fuel load and more likely due to excess burning (of combustible vapors from fire-heated office furnishings) near the windows relative to the burning in the building interior.

4.3.3 Fire-induced Thermal Effects

- Calculated fire-elevated temperatures in the interior columns, including Columns 79, 80, and 81, stayed below 200 ºC on all of the floors. The exterior column temperatures were below 150 ºC, except on Floors 12 and 13, where the east and south exterior columns reached 300 ºC. At these temperatures, structural steel experiences relatively little loss of strength or stiffness. Thus, WTC 7 did not collapse due to fire-induced weakening of critical columns.

- The simulated fires on Floors 7, 12, and 13 heated portions of the tops of the floor slabs to over 900 ºC. The temperatures of some sections of the beams supporting Floors 8, 12, 13, and 14 exceeded 600 ºC. The temperatures of some sections of the floor beams at Floors 9 and 10 reached 400 ºC.

- Raising the fire-generated air temperatures by 10 percent, which was within the range of reasonable and realistic fires, raised the peak temperatures in the floor beams and slabs by about 70 ºC. Additionally, the areas over which the temperatures of the floor beams exceeded 600 ºC increased. Comparable changes in the opposite direction resulted from lowering the fire-generated air temperatures (Case A).

4.3.4 Structural Response and Collapse

Initiating Event

- The buckling failure of Column 79 between Floor 5 and Floor 14 was the initiating event that led to the global collapse of WTC 7. This resulted from thermal expansion and failures of connections, beams, and girders in the adjacent floor systems.

- The connection, beam, and girder failures in the floor systems, and the resulting structural responses, occurred at temperature below approximately 400 °C, well below the temperatures at which structural steel loses significant strength and stiffness.

- Thermal expansion was particularly significant in causing the connection, beam, and girder failures, since the floor beams had long spans on the north and east sides (approximately 15 m, 50 ft).

    - Heating of the long beams resulted in proportionately large thermal elongation relative to the other components of the floor system, in effect, compressing the beams along their length. This led to distortion of the beams and breaking of the connections of the beams to the floor slabs. Furthermore, the simple shear connections used in the typical floor framing were not able to resist these axial compressive forces that developed as the floor framing was heated.

    - At Column 79, heating and expansion of the floor beams in the northeast corner caused the loss of connection between the column and the key girder. Additional factors that contributed to the failure of the critical north-south girder were (1) the absence of shear studs that would have provided lateral restraint and (2) the one-sided framing of the east floor beams that allowed the beams to push laterally on the girders, due to thermal expansion of the beams.

    - The fires thermally weakened Floors 8 to 14. As Floor 13 fell onto the floor below, a cascade of floor failures continued until the damage reached the massive Floor 5 slab, leaving Column 79 without lateral support for nine floors. The long unsupported length of Column 79 led to its buckling failure.

- Hypothetical blast events did not play a role in the collapse of WTC 7. NIST concluded that blast events could not have occurred, and found no evidence whose explanation required invocation of a blast event. Blast from the smallest charge capable of failing a critical column (i.e., Column 79) would have resulted in a sound level of 130 dB to 140 dB at a distance of at least half a mile if unobstructed by surrounding buildings (such as along Greenwich Street and West Broadway). This sound level is comparable to a gunshot blast, standing next to a jet plane engine, and more than 10 times louder than being in front of the speakers at a rock concert. The sound from such a blast in an urban setting would have been reflected and channeled down streets with minimum attenuation. However, the soundtracks from videos being recorded at the time of the collapse did not contain any sound as intense as would have accompanied such a blast

Vertical Progression of Collapse

- Once Column 79 buckled, there was a vertical progression of floor system failures up to the east penthouse, followed by the buckling of Columns 80 and 81.
  - The buckling of Column 79 at the lower floors led to downward movement of the upper section of Column 79. The adjacent floor framing was pulled downward, leading to the observed kink in the east penthouse roof framing.
  - As the lower floors surrounding Column 79 fell downward, Column 80 and Column 81 had increased unsupported lengths as well as falling debris impacts and loads being redistributed from adjacent columns. This led to buckling of Columns 80 and 81, and resulted in a vertical progression of failure of the floor systems up to the roof level across the entire east side of WTC 7.
- Columns 79, 80, and 81 were the only interior support for the gravity loads in the eastern region of the building. Once these three columns buckled and their upper sections began to descend, there was insufficient support for the floors, up to the east penthouse.
- None of these columns were significantly weakened by elevated temperatures; temperatures did not exceed 300 °C in the core or perimeter columns in WTC 7.

Horizontal Progression of Collapse

- Columns 76 through 78 were the next line of columns to buckle, due to loss of lateral support, impact by falling debris, and load redistribution from Columns 79 through 81. The failure of Truss 2 was not essential to the failure of Columns 77 and 78, as they would have buckled like the other columns.
- The remaining interior columns buckled in succession from east to west in the lower floors due to loss of lateral support from floor system failures, forces exerted by falling debris impact, and load redistributed to them from other buckled columns.
- The initial westward progression and the overall speed of the collapse was not sensitive to the extent of the estimated structural damage to WTC 7 due to the debris from the collapse of WTC 1. When the global collapse was nearly complete, there was some small sensitivity to the extent of the initial damage in the southwest portion of the building.

Global Collapse

- The exterior columns buckled at the lower floors (between Floors 7 and 14) due to load redistribution to the exterior columns from the building core as the interior columns buckled and the building core moved downward. The entire building above the buckled-column region then moved downward in a single unit, as observed, completing the global collapse sequence.

- Computer simulations of the fires, the thermal heating of the structure, the thermally induced damage to the structure, and the structural collapse can be used to predict a complex degradation and collapse of a building. The overall features and timing of the prediction were consistent with the videographic evidence.

- The uncertainties in predicting the precise progression of the collapse sequence increased as the analysis proceeded due to the random nature of the interaction, break up, disintegration, and falling of the debris. The uncertainties deriving from these random processes increasingly influence the deterministic physics-based collapse process. Thus, the details of the progression of horizontal failure and final global collapse were sensitive to the uncertainties in how the building materials (steel, concrete) and building systems and contents interacted, broke up, and disintegrated

- These computational models comprise a set of research tools that can take months (eight months in this case) for a complete simulation. Their adaptation for engineering practice would forestall future disasters, while reducing the potential for structural overdesign.

4.4 LIFE SAFETY FACTORS

4.4.1 Evacuation of WTC 7

- By the conventional measure of life safety, the evacuation of WTC 7 was successful, as NIST identified no life-threatening injuries or fatalities among the estimated 4,000 building occupants on September 11, 2001.

- Most of the occupants initiated their own evacuation shortly after WTC 1 was attacked.

- Evacuation of the building took just over an hour to complete, which was about 30 min longer than the estimated minimum time if the elevators and stairs had been used to maximum advantage. Nonetheless, the building was safely evacuated prior to the collapse of WTC 2. Some of the additional evacuation time was due to the considerable crowding in the lobby. Occupants arrived in the lobby from both stairwells, from the elevators, and from other WTC buildings, and were held in the lobby until a safe exterior exit was identified by emergency management officials.

- The calculated stairwell capacity was insufficient to meet the requirements of the NYCBC in effect during the design and construction period, if the building were occupied at the calculated maximum level (≈ 14,000 people). The capacity was sufficient for the normal occupancy of the building (≈ 8,000 workers plus visitors), estimated by NIST, and was more than sufficient for the occupancy on September 11, 2001 (≈ 4,000 people), also estimated by NIST. The stairwell capacity met the requirement of the (subsequent) 2000 edition of the IBC, but not the 2003 edition of NFPA 5000.

- The separation of the stairwell doors met the requirement of the 1968 NYCBC. On some floors, the separation of the stairwell doors was below the remoteness requirements in the (current) 2000 IBC and the 2003 NFPA 5000.

- Evacuation management at every level did not provide timely evacuation instructions to building occupants during the event. NIST was not able to determine whether specific guidance was delivered to the occupants via the public address system.

- In addition to the length of time that WTC 7 withstood the internal fires, some specific people actions likely contributed to the speed and overall success of the evacuation.

  - Evacuation drills had been conducted every six months.

  - The decision to prevent occupants from exiting the stairwells out into the streets where they could be impacted by debris from WTC 1 and WTC 2 likely prevented injuries or deaths.

  - Using the loading dock exit to provide overhead protection, combined with the scaffolding protection along the other side of Washington Street, was an example of spontaneous decision-making on the part of the building management personnel which likely contributed to the positive outcome.

4.4.2 Emergency Response

- Faced with a disaster of an unprecedented nature, the involvement of the emergency management personnel with regard to WTC 7 was limited. Nonetheless, no lives were lost as a result of the collapse of WTC 7.

- The loss of numerous firefighters, company officers, and chief officers in the collapses of WTC 1 and WTC 2 led to a changing command structure for the rest of the morning, as new command posts were established and several different chief officers took command and relinquished command of operations at the WTC site.

- Due to the focus on rescuing people trapped in the debris field, providing aid to the injured, and the loss of water in the hydrant system, FDNY was not able to consider the possibility of fighting the fires in WTC 7 until approximately 1:00 p.m. At approximately 2:30 p.m., FDNY gave the order to forego firefighting activity and for personnel to withdraw to a safe distance from the building.

- Con Edison shut of all power to the substation under WTC 7 at 4:33 p.m.

4.5 CODES, STANDARDS, AND PRACTICES

4.5.1 General

- WTC 7 was designed and constructed as a “Tenant alteration project” of The Port Authority. Its design and construction followed the requirements of the 1984 edition of the Tenant Construction Review Manual.

- Although the PANYNJ was not subject to the NYCBC, the 1968 NYCBC, including amendments to January 1, 1985, appears to have been used for the design and construction provisions of WTC 7, based on citations in the construction documents.

- The type of building classification used to design and construct the building was not clear from the available documents. Based on the height, area, primary occupancy classification, and installation of a fire sprinkler and standpipe system, the minimum construction type (permitted by NYCBC) was type 1-C (2 h protected) classification. However, some documentation, including some building drawings and specifications for bidders on the contract for applying SFRM to the structural steel, indicate a type 1-B (3 h protected) classification.

4.5.2 Building Design and Structural Safety

- NIST found no evidence to suggest that WTC 7 was not designed in a manner generally consistent with applicable building codes and standards.
- WTC 7 was adequately designed for vertical loads due to gravity and lateral loads due to wind.

  - The vertical (gravity) load resisting system comprised the core and exterior columns, which received gravity loads from the floor framing. Of particular note were the three core columns on the east side of the building (Columns 79, 80, and 81), which supported large span floor areas with approximately 15 m (50 ft) spans on at least one side.

  - Above Floor 7, the lateral load resisting system comprised the exterior moment frame with a perimeter belt truss at Floors 22 through 24. There were also a perimeter belt truss between Floors 5 and 7, diaphragms at Floors 5 and 7 that transferred lateral wind loads to the core columns, and bracing in the core below Floor 7 that transferred lateral loads to the foundation. However, this system was not able to provide a secondary load path for gravity loads.

  - Above Floor 7, there was no bracing, or other load redistribution mechanism, to transfer gravity loads between interior columns. The floor framing, which was the only load path between columns, could not redistribute loads between columns because the shear connections from the interior floor beams to columns were only designed for transferring vertical shear loads.

  - Transfer girders, trusses, and cantilever overlays were used to transfer column loads above Floor 7 to a different column layout below Floor 5.

- The structural design did not explicitly evaluate fire effects, which was typical for engineering practice at that time and continues to remain so today. Many of the shear connections in WTC 7 were not capable of resisting lateral loads resulting from thermal expansion effects in the steel floor framing when the floor beams were heated.

4.5.3 SFRM Requirements and Application

- It is likely that the Monokote MK-5 SFRM, applied to the steel framing and metal decks, was undamaged by the impact of the debris from the collapse of WTC 1, except in the area where direct structural damage to WTC 7 occurred.

- NIST simulations showed that, for the heaviest columns in WTC 7, when properly insulated, it would have taken an exposure of about 7 h at post-flashover upper layer gas temperatures to raise the steel temperature to 600 ºC, the point at which the steel strength would have been reduced by half. A similar calculation indicated it would have taken about 4 h to reach this temperature for an insulated lighter column. These times are both far longer than the time over which post-flashover gas temperatures were sustained in the computed WTC 7 fires. For comparison, this steel temperature would have been reached in under one-half hour if the insulation were not applied.

- It is unlikely that the collapse of WTC 7 would have been prevented had the insulation thickness on the floor beams been increased by 50 percent (from ½ in. to ¾ in.). NIST calculations indicated that the time to reach the steel temperature of 649 °C (1200 °F) would have increased by about 10 min to 20 min.

- The ASTM E119 test does not capture critical behavior of structural systems, e.g., the effect of thermal expansion or sagging of floor beams on girders, connections, and/or columns. The thermal expansion of the WTC 7 floor beams that initiated the probable collapse sequence occurred at temperatures below approximately 400 °C. Thus, to the extent that thermal expansion, rather than loss of structural strength, precipitates an unsafe condition, thermal expansion effects need to be evaluated. The current fire resistance rating system, which does not include thermal expansion effects, is not conservative.

4.5.4 Fire Safety and Fire Protection Systems

- WTC 7 had the following active fire protection systems: fire alarms, smoke and heat detectors, manual pull stations, smoke control systems, and automatic sprinklers. Each was designed, constructed, and apparently maintained consistent with applicable building codes and standards.
- The standpipe and automatic sprinkler systems were divided into three zones. As prescribed by the NYCBC, each zone had a primary and secondary water supply.
    - The primary water supply for the high zone (Floors 40 through 47) and mid-level zone (Floors 21 through 39) was from two water storage tanks on the 46th floor. The secondary supply was pumped from the city water main.

    - The primary water supply for the low zone, floors 1 through 20, was a direct connection to the city water mains. The secondary supply was from an automatic fire pump, which was connected to the city water main as well.

- Since the city water main had been compromised as a result of the collapses of the two towers, there was no water supply to control the fires on the 7th through 13th floors. By contrast, the early

fires on the 22nd, 29th, and 30th floors may have been controlled by the sprinkler system on the upper floors, whose primary water supply was from the storage tanks on the 46th floor.

- The architectural drawings indicated that there were fire-rated walls between tenant spaces on the same floor and between tenant spaces and the building core. Spaces housing mechanical equipment, power transformers, emergency power generators, and other such equipment were enclosed in fire-rated partitions. While the partitions between offices, conferences rooms, etc. were not required to be fire-rated, there was evidence from both the visual evidence and the fire simulations that some of these partitions did retard the spread of the fires.

- There was no evidence of floor-to-floor fire spread until perhaps just before the WTC 7 collapse. Thus, the fire-rated floors were successful as fire penetration barriers.

4.6 FUTURE FACTORS THAT COULD HAVE MITIGATED STRUCTURAL COLLAPSE

In the course of the Investigation, NIST and its contractors were aware that there were existing, emerging, or even anticipated capabilities that could have prevented the collapse of WTC 7, had they been in place on September 11, 2001. NIST has not conducted studies to evaluate the degree to which building performance could have been improved on September 11, 2001, had the capabilities been available. These include:

- More robust connections and framing systems to better resist the effects of thermal expansion on the structural system.

- Structural systems expressly designed to prevent progressive collapse. The current model building codes do not require that buildings be designed to resist progressive collapse.

- Better thermal insulation (i.e., reduced conductivity and/or increased thickness) to limit heating of structural steel and to minimize both thermal expansion and weakening effects. Currently, insulation is used to protect steel strength, but it could also be used to maintain a lower temperature in the steel framing to limit thermal expansion.

- Automatic fire sprinkler systems with independent and reliable sources for the primary and secondary water supply.

- Improved compartmentation in tenant areas to limit the spread of fires.

- Thermally resistant window assemblies which limit breakage, reduce air supply, and retard fire growth.

4.7 HUMAN PERFORMANCE FACTORS

There were factors that contributed to the outcome of no loss of life at WTC 7.

- Reduced number of people in WTC 7 at the times of airplane impact on the towers.

- Shortness of delay in starting to evacuate.
- Evacuation assistance provided by emergency responders to evacuees.
- Participation of the building occupants in recent fire drills.
- Decision not to continue reconnaissance of the building and not to fight the fires within.

There were also factors that did not play a life safety role in WTC 7 on September 11, 2001, but could have been important had the fires been more widespread, the building damage more severe, or the building occupancy at full capacity.

- Accuracy and reliability of communications among emergency responders and building occupants.
- Efficiency of management of large-scale emergency incidents.

Chapter 5
RECOMMENDATIONS

5.1 GENERAL

In its final report on the collapse of the World Trade Center towers (NIST NCSTAR 1), NIST made 30 recommendations for improving the safety of buildings, occupants, and emergency responders. These encompass increased structural integrity, enhanced fire endurance of structures, new methods for fire resistant design of structures, improved active fire protection, improved building evacuation, improved emergency response, improved procedures and practices, and education and training.

WTC 7 was unlike the WTC towers in many respects. It was a more typical tall building in the design of its structural system. It was not struck by an airplane. The fires in WTC 7 were quite different from those in the towers. Since WTC 7 was not doused with thousands of gallons of jet fuel, large areas of any floor were not ignited simultaneously. Instead, the fires in WTC 7 were similar to those that have occurred previously in several tall buildings where the sprinklers did not function or were not present. These other buildings did not succumb to their fires and collapse because they were of structural designs that differed from that of WTC 7.

The Investigation Team has compiled a list of key factors that enabled ordinary fires to result in an extraordinary outcome. In so doing, the Team recognized that there were additional aspects to be included in the content of some of the 30 earlier recommendations.

Based on the findings of this Investigation, NIST has identified one new recommendation and has reiterated 12 recommendations from the Investigation of the WTC towers.

The urgency of the prior recommendations is substantially reinforced by their pertinence to the collapse of a tall building that is based on a structural system design that is in widespread use. A few of the prior recommendations have been modified to reflect the findings of this Investigation.

The partial or total collapse of a building due to fires is an infrequent event. This is particularly true for buildings with a reliably operating active fire protection system such as an automatic fire sprinkler system. A properly designed and operating automatic sprinkler system will contain fires while they are small and, in most instances, prevent them from growing and spreading to threaten structural integrity.

The intent of current practice, based on prescriptive standards and codes, is to achieve life safety, not collapse prevention. However, the key premise of NIST's recommendations is that buildings should not collapse in infrequent (worst-case) fires that may occur when active fire protection systems are rendered ineffective, e.g., when sprinklers do not exist, are not functional, or are overwhelmed by the fire.

Fire scenarios for structural design based on single compartment or single floor fires are not appropriate representations of infrequent fire events. Such events have occurred in several tall buildings resulting in unexpected substantial losses. Instead, historical data suggests that infrequent fires which should be considered in structural design have characteristics that include: ordinary combustibles and combustible

load levels, local fire origin on any given floor, no widespread use of accelerants, consecutive fire spread from combustible to combustible, fire-induced window breakage providing ventilation for continued fire spread and accelerated fire growth, concurrent fires on multiple floors, and active fire protection systems rendered ineffective. The fires in WTC 7 had all of these characteristics.

NIST believes the recommendations are realistic, appropriate, and achievable within a reasonable period of time. NIST strongly urges that immediate and serious consideration be given to these recommendations by the building and fire safety communities in order to achieve appropriate improvements in the way buildings are designed, constructed, maintained, and used—with the goal of making buildings safer in future emergencies.

A complete listing of all 13 recommendations (Recommendations A through L) based on this Investigation follows. Under a few of the recommendations, the pertinent lesson from the reconstruction of the WTC 7 collapse is reflected in the form of a modification. For the 12 reiterated recommendations, the pertinent codes, standards, and organizations were listed in Table 9-1 and Tables 9-2a through 9-2c of NIST NCSTAR 1 and are not repeated here. For the one new recommendation, B, this information is provided in the text below.

NIST'S RECOMMENDATIONS FOR IMPROVING THE SAFETY OF BUILDINGS, OCCUPANTS, AND EMERGENCY RESPONDERS

5.1.1 Group 1. Increased Structural Integrity

The standards for estimating the load effects of potential hazards (e.g., progressive collapse, wind) and the design of structural systems to mitigate the effects of those hazards should be improved to enhance structural integrity.

> **Recommendation A (NIST NCSTAR 1 Recommendation 1). NIST recommends that: (1) progressive collapse be prevented in buildings through the development and nationwide adoption of consensus standards and code provisions, along with the tools and guidelines needed for their use in practice; and (2) a standard methodology be developed—supported by analytical design tools and practical design guidance—to reliably predict the potential for complex failures in structural systems subjected to multiple hazards.**
>
> *Relevance to WTC 7:* Had WTC 7 been expressly designed for prevention of fire-induced progressive collapse, it would have been sufficiently robust to withstand local failure due to the fires without suffering total collapse.

5.1.2 Group 2. Enhanced Fire Endurance of Structures

The procedures and practices used to ensure the fire endurance of structures should be enhanced by improving the technical basis for construction classifications and fire resistance ratings, improving the technical basis for standard fire resistance testing methods, use of the "structural frame" approach to fire resistance ratings, and developing in-service performance requirements and conformance criteria for sprayed fire-resistive materials.

> **Recommendation B (New), NIST recommends that buildings be explicitly evaluated to ensure the adequate performance of the structural system under worst-case design fires with any**

active fire protection system rendered ineffective. Of particular concern are the effects of thermal expansion in buildings with one or more of the following features: (1) long-span floor systems[6] which experience significant thermal expansion and sagging effects, (2) connection designs (especially shear connections) that cannot accommodate thermal effects, (3) floor framing that induces asymmetric thermally-induced (i.e., net lateral) forces on girders, (4) shear studs that could fail due to differential thermal expansion in composite floor systems, and (5) lack of shear studs on girders. Careful consideration should also be given to the possibility of other design features that may adversely affect the performance of the structural system under fire conditions.

Building owners, operators, and designers are strongly urged to act upon this recommendation. Engineers should be able to design cost-effective fixes to address any areas of concern that are identified by these evaluations. Several existing, emerging, or even anticipated capabilities could have helped prevent the collapse of WTC 7. The degree to which these capabilities improve performance remains to be evaluated. Possible options for developing cost-effective fixes include:

- More robust connections and framing systems to better resist the effects of thermal expansion on the structural system.
- Structural systems expressly designed to prevent progressive collapse. The current model building codes do not require that buildings be designed to resist progressive collapse.
- Better thermal insulation (i.e., reduced conductivity and/or increased thickness) to limit heating of structural steel and to minimize both thermal expansion and weakening effects. Currently, insulation is used to protect steel strength, but it could also be used to maintain a lower temperature in the steel framing to limit thermal expansion.
- Improved compartmentation in tenant areas to limit the spread of fires.
- Thermally resistant window assemblies which limit breakage, reduce air supply, and retard fire growth.

Industry should partner with the research community to fill critical gaps in knowledge about how structures perform in real fires, particularly considering: the effects of fire on the entire structural system; the interactions between subsystems, elements, and connections; and scaling of fire test results to full-scale structures, especially for structures with long span floor systems.

Affected Standards: ASCE 7, ASCE/SFPE 29, AISC Specifications, ACI 318. Development of performance objectives, design criteria, evaluation methods, design guidance, and computational tools should begin promptly, leading to new standards.

Model Building Codes: The new standard should be adopted in model building codes (IBC, NFPA 5000) by mandatory reference to, or incorporation of, the latest edition of the standard.

[6] Typical floor span lengths in tall office buildings are in the range of 40 ft to 50 ft; this range is considered to represent long-span floor systems. Thermal effects (e.g., thermal expansion) that may be significant in long-span buildings may also be present in buildings with shorter span lengths, depending on the design of the structural system.

Relevance to WTC 7: The effects of restraint of free thermal expansion on the steel framing systems, especially for the long spans on the east side of WTC 7, were not considered in the structural design and led to the initiation of the building collapse.

Recommendation C (NIST NCSTAR 1 Recommendation 4). NIST recommends evaluating, and where needed improving, the technical basis for determining appropriate construction classification and fire rating requirements (especially for tall buildings)—and making related code changes now as much as possible—by explicitly considering factors including:[7]

- **timely access by emergency responders and full evacuation of occupants, or the time required for burnout without partial collapse;**
- **the extent to which redundancy in active fire protection (sprinkler and standpipe, fire alarm, and smoke management) systems should be credited for occupant life safety;**[8]
- **the need for redundancy in fire protection systems that are critical to structural integrity;**[9]
- **the ability of the structure and local floor systems to withstand a maximum credible fire scenario**[10] **without collapse, recognizing that sprinklers could be compromised, not operational, or non-existent;**
- **compartmentation requirements (e.g., 12,000 ft^2** [11]**) to protect the structure, including fire rated doors and automatic enclosures, and limiting air supply (e.g., thermally resistant window assemblies) to retard fire spread in buildings with large, open floor plans;**
- **the effect of spaces containing unusually large fuel concentrations for the expected occupancy of the building; and**
- **the extent to which fire control systems, including suppression by automatic or manual means, should be credited as part of the prevention of fire spread.**

Relevance to WTC 7: The floor systems in WTC 7 failed at lower temperatures because thermal effects within the structural system, especially thermal expansion, were not considered in setting the fire rating requirements in the construction classification, which are determined using the ASTM E 119 or equivalent testing standard.

---

7 The construction classification and fire rating requirements should be *risk-consistent* with respect to the *design-basis hazards* and the *consequences* of those hazards. The fire rating requirements, which were originally developed based on experience with buildings fewer than 20 stories in height, have generally decreased over the past 80 years since historical fire data for buildings suggests considerable conservatism in those requirements. For tall buildings, the likely consequences of a given threat to an occupant on the upper floors are more severe than the consequences to an occupant on the first floor or the lower floors. For example, with non-functioning elevators, both the time requirements are much greater for full building evacuation from upper floors and emergency responder access to those floors. The current height and areas tables in building codes do not provide the technical basis for the progressively increasing risk to an occupant on the upper floors of tall buildings that are much greater than 20 stories in height.

8 Occupant life safety, prevention of fire spread, and structural integrity are considered separate safety objectives.

9 The passive fire protection system (including the application of SFRM, compartmentation, and firestopping) and the active sprinkler system each provide redundancy for maintaining structural integrity in a building fire, should one of the systems fail to perform its intended function.

10 A maximum credible fire scenario includes conditions that are severe, but reasonable to anticipate, conditions related to building construction, occupancy, fire loads, ignition sources, compartment geometry, fire control methods, etc., as well as adverse, but reasonable to anticipate operating conditions.

11 Or a more appropriate limit, which represents a reasonable area for active firefighting operations.

<u>Recommendation D</u> (NIST NCSTAR 1 Recommendation 5). NIST recommends that the technical basis for the century-old standard for fire resistance testing of components, assemblies, and systems be improved through a national effort. Necessary guidance also should be developed for extrapolating the results of tested assemblies to prototypical building systems. A key step in fulfilling this recommendation is to establish a capability for studying and testing the components, assemblies, and systems under realistic fire and load conditions.

Of particular concern is that the Standard Fire Resistance Test does not adequately capture important thermally-induced interactions between structural subsystems, elements, and connections that are critical to structural integrity. System-level interactions, especially due to thermal expansion, are not considered in the standard test method since columns, girders, and floor subassemblies are tested separately. Also, the performance of connections under both gravity and thermal effects is not considered. The United States currently does not have the capability for studying and testing these important fire-induced phenomena critical to structural safety.

Relevance to WTC 7: The floor systems failed in WTC 7 at shorter fire exposure times than the specified fire rating (two hours) and at lower temperatures because thermal effects within the structural system, especially thermal expansion, were not considered in setting the endpoint criteria when using the ASTM E 119 or equivalent testing standard. The structural breakdowns that led to the initiating event and the eventual collapse of WTC 7 occurred at temperatures that were hundreds of degrees below the criteria that determine structural fire resistance ratings.

<u>Recommendation E</u> (NIST NCSTAR 1 Recommendation 7). NIST recommends the adoption and use of the "structural frame" approach to fire resistance ratings. This approach requires all members that comprise the primary structural frame (such as columns, girders, beams, trusses, and spandrels) be fire protected to the higher fire resistance rating required for the columns. The definition of the primary structural frame should be expanded to include bracing members that are essential to the vertical stability of the primary structural frame under gravity loading (e.g. girders, diagonal bracing, composite floor systems that provide lateral bracing to the girders) whether or not the bracing members carry gravity loads. Some of these bracing members may not have direct connections to the columns, but provide stability to those members directly connected to the columns. This recommendation modifies the definition of the primary structural frame adopted in the 2007 supplement to the International Building Code (IBC). The IBC considers members of floor or roof construction that are not connected to the columns to not be part of the primary structural frame. This recommendation ensures consistency in the fire protection provided to all of the structural elements that contribute to overall structural stability. State and local jurisdictions should adopt and enforce this requirement.

Relevance to WTC 7: Thermally-induced breakdown of the floor system in WTC 7 was a determining step in causing collapse initiation and progression. Therefore, the floor system should be considered as an integral part of the primary structural frame.

5.1.3 Group 3. New Methods for Fire Resistant Design of Structures

The procedures and practices used in the fire resistant design of structures should be enhanced by requiring an objective that uncontrolled fires result in burnout without partial or global (total) collapse. Performance-based methods are an alternative to prescriptive design methods. This effort should include the development and evaluation of new fire-resistive coating materials and technologies and evaluation of the fire performance of conventional and high-performance structural materials.

__Recommendation F (NCSTAR Recommendation 8).__ **NIST recommends that the fire resistance of structures be enhanced by requiring a performance objective that uncontrolled building fires result in burnout without partial or global (total) collapse.** Such a provision should recognize that sprinklers could be compromised, non-operational, or nonexistent. Current methods for determining the fire resistance rating of structural assemblies do not explicitly specify a performance objective. The rating resulting from current test methods indicates that the assembly (component or subsystem) continued to support its superimposed load (simulating a maximum load condition) during the test exposure without collapse. *Model Building Codes:* This recommendation should be included into the national model codes as an objective and adopted as an integral part of fire resistance design for structures. The issue of non-operational sprinklers could be addressed using the existing concept of Design Scenario 8 of NFPA 5000, where such compromise is assumed and the result is required to be acceptable to the Authority Having Jurisdiction. *Affected Standards:* ASCE-7, AISC Specifications, ACI 318, and ASCE/SFPE 29.

Relevance to WTC 7: Large, uncontrolled fires led to failure of a critical column and consequently the complete collapse of WTC 7. In the region of the collapse initiation (i.e., on the east side of Floor 13), the fire had consumed virtually all of the combustible building contents, yet collapse was not prevented.

__Recommendation G (NIST NCSTAR 1 Recommendation 9).__ **NIST recommends the development of: (1) performance-based standards and code provisions, as an alternative to current prescriptive design methods, to enable the design and retrofit of structures to resist real building fire conditions, including their ability to achieve the performance objective of burnout without structural or local floor collapse: and (2) the tools, guidelines, and test methods necessary to evaluate the fire performance of the structure as a whole system.** Standards development organizations, including the American Institute of Steel Construction, have already begun developing performance-based provisions to consider the effects of fire in structural design.

This performance-based capability should include the development of, but not be limited to:

a. Standard methodology, supported by performance criteria, analytical design tools, and practical design guidance; related building standards and codes for fire resistance design and retrofit of structures, working through the consensus process for nationwide adoption; comprehensive design rules and guidelines; methodology for evaluating thermostructural performance of structures; and computational models and analysis procedures for use in routine design practice.

b. Standard methodology for specifying multi-compartment, multi-floor fire scenarios for use in the design and analysis of structures to resist fires, accounting for building-specific conditions such as geometry, compartmentation, fuel load (e.g., building contents and any flammable fuels such as oil and gas), fire spread, and ventilation; and methodology for rating the fire resistance of structural systems and barriers under realistic design-basis fire scenarios.

c. Publicly available computational software to predict the effects of fires in buildings—developed, validated, and maintained through a national effort—for use in the design of fire protection systems and the analysis of building response to fires. Improvements should include the fire behavior and contribution of real combustibles; the performance of openings, including door openings and window breakage, that controls the amount of oxygen available to support the growth and spread of fires and whether the fire is fuel-controlled or ventilation-controlled; the floor-to-floor flame spread; the temperature rise in both insulated and uninsulated structural members and fire barriers; and the structural response of components, subsystems, and the total building system due to the fire.

d. Temperature-dependent thermal and mechanical property data for conventional and innovative construction materials

e. New test methods, together with associated conformance assessment criteria, to support the performance-based methods for fire resistance design and retrofit of structures. The performance objective of burnout without collapse will require the development of standard fire exposures that differ from those currently used.

There is a critical gap in knowledge about how structures perform in real fires, particularly considering: the effects of the fire on the entire structural system (including thermal expansion effects at lower temperatures); the interaction between the subsystems, elements, and connections; and scaling of fire test results to full-scale structures (especially for structures with long span floor system).

Relevance to WTC 7: A performance-based assessment of the effects of fire on WTC 7, had it considered all of the relevant thermal effects (e.g., thermal expansion effects that occur at lower temperatures), would have identified the vulnerability of the building to fire-induced collapse and allowed alternative designs for the structural system.

5.1.4 Group 4. Improved Active Fire Protection

Active fire protection systems (i.e., sprinklers, standpipes/hoses, fire alarms, and smoke management systems) should be enhanced through improvements to design, performance, reliability, and redundancy of such systems.

<u>Recommendation H (NIST NCSTAR 1 Recommendation 12).</u> NIST recommends that the performance and possibly the redundancy and reliability of active fire protection systems (sprinklers, standpipes/hoses, fire alarms, and smoke management systems) in buildings be enhanced to accommodate the greater risks associated with increasing building height and population, increased use of open spaces, high-risk building activities, fire department response limits, transient fuel loads, and higher threat profile.

Reliability is affected by (a) the redundancy such that one water supply is out of service (usually for maintenance) the other interconnected water supply can continue to protect the building and its occupants, (b) automatic operation of water supply systems (not only for starting fire pumps but also for testing and tank replenishment with appropriate remote alarms to the fire department and local alarms for notifying emergency personnel), (c) the use of suitable equipment and techniques to regulate unusual pressure considerations.

Relevance to WTC 7: No water was available for the automatic suppression system on the lower 20 stories of WTC 7 once water from street-level mains was disrupted. This lack of reliability in the source of the primary and secondary water supply allowed the growth and spread of fires that ultimately resulted in collapse of the building.

5.1.5 Group 6. Improved Emergency Response

Technologies and procedures for emergency response should be improved to enable better access to buildings, response operations, emergency communications, and command and control in large-scale emergencies.

<u>Recommendation I (NIST NCSTAR 1 Recommendation 24).</u> NIST recommends the establishment and implementation of codes and protocols for ensuring effective and uninterrupted operation of the command and control system for large-scale building emergencies.

a. State, local, and federal jurisdictions should implement National Incident Management System. The jurisdictions should work with the Department of Homeland Security to review, test, evaluate, and implement an effective unified command and control system. NIMS addresses interagency coordination and establishes a response matrix—assigning lead agency responsibilities for different types of emergencies and functions. At a minimum, each supporting agency should assign an individual to provide coordination with the lead agency at each incident command post.

b. State, local, and federal emergency operations centers (EOCs) should be located, designed, built, and operated with security and operational integrity as a key consideration.

c. Command posts should be established outside the potential collapse footprint of any building which shows evidence of large multi-floor fires or has serious structural damage. A continual assessment of building stability and safety should be made in such emergencies to guide ongoing operations and enhance emergency responder safety. The information necessary to make these assessments should be made available to those assigned responsibility (see related Recommendations 15 and 23 in NIST NCSTAR 1).

d. An effective command system should be established and operating before a large number of emergency responders and apparatus are dispatched and deployed. Through training and drills, emergency responders and ambulances should be required to await dispatch requests from the incident command system and not to self-dispatch in large-scale emergencies.

e. Actions should be taken via training and drills to ensure a coordinated and effective emergency response at all levels of the incident command chain by requiring all emergency responders that are given an assignment to immediately adopt and execute the assignment objectives.

f. Command post information and incident operations data should be managed and broadcast to command and control centers at remote locations so that information is secure and accessible by all personnel needing the information. Methods should be developed and implemented so that any information that is available at an interior information center is transmitted to a emergency responder vehicle or command post outside the building.

Relevance to WTC 7: (1) The New York City Office of Emergency Management (OEM) was located in WTC 7 and was evacuated before key fire ground decisions had to be made. The location of OEM in WTC 7, which collapsed due to ordinary building fires, contributed to the loss of robust interagency command and control on September 11, 2001. (2) Due to the collapse of the WTC towers and the loss of responders and fire control resources, there was an evolving site leadership during the morning and afternoon. Key decisions (e.g., decisions not to fight the fires in WTC 7 and to turn off the power to the Con Edison substation) were reasonable and would not have changed the outcome on September 11, 2001, but were not made promptly. Under different circumstances (e.g., if WTC 7 had collapsed sooner and fire fighters were still evaluating the building condition), the outcome could have been very different.

5.1.6 Group 7. Improved Procedures and Practices

The procedures and practices used in the design, construction, maintenance, and operation of buildings should be improved to include encouraging code compliance by nongovernmental and quasi-governmental entities, adoption and application of egress and sprinkler requirements in

codes for existing buildings, and retention and availability of building documents over the life of a building.

<u>Recommendation J (NIST NCSTAR 1 Recommendation 27).</u> NIST recommends that building codes incorporate a provision that requires building owners to retain documents, including supporting calculations and test data, related to building design, construction, maintenance and modifications over the entire life of the building.[12] Means should be developed for offsite storage and maintenance of the documents. In addition, NIST recommends that relevant building information be made available in suitably designed hard copy or electronic format for use by emergency responders. Such information should be easily accessible by responders during emergencies.

Relevance to WTC 7: The efforts required in locating and acquiring drawings, specifications, tenant layouts, and material certifications, and especially shop fabrication drawings, significantly lengthened the investigation into the collapse of WTC 7.

<u>Recommendation K (NIST NCSTAR 1 Recommendation 28).</u> NIST recommends that the role of the "Design Professional in Responsible Charge"[13] be clarified to ensure that: (1) all appropriate design professionals (including, e.g., the fire protection engineer) are part of the design team providing the standard of care when designing buildings employing innovative or unusual fire safety systems, and (2) all appropriate design professionals (including, e.g., the structural engineer and the fire protection engineer) are part of the design team providing the standard of care when designing the structure to resist fires, in buildings that employ innovative or unusual structural and fire safety systems.

Relevance to WTC 7: Following typical practice, none of the design professionals in charge of the WTC 7 project (i.e., architect, structural engineer, and fire protection engineer) was assigned the responsibility to explicitly evaluate the fire performance of the structural system. Holistic consideration of thermal and structural factors during the design or review stage could have identified the potential for the failure and might have prevented the collapse of the building.

5.1.7 Group 8. Education and Training

The professional skills of building and fire safety professionals should be upgraded through a national education and training effort for fire protection engineers, structural engineers, and architects. The skills of the building regulatory and fire service personnel should also be upgraded to provide sufficient understanding and the necessary skills to conduct the review, inspection, and approval tasks for which they are responsible.

<u>Recommendation L (NIST NCSTAR 1 Recommendation 29).</u> NIST recommends that continuing education curricula be developed and programs be implemented for (1) training fire protection engineers and architects in structural engineering principles and design, and (2) training structural engineers, architects, fire protection engineers, and code enforcement officials in modern fire protection principles and technologies, including fire-resistance design of structures, and (3) training building regulatory and fire service personnel to upgrade their

---

[12] The availability of inexpensive electronic storage media and tools for creating large searchable databases make this feasible.

[13] In projects involving a design team, the "Design Professional in Responsible Charge"—usually the lead architect—ensures that the team members use consistent design data and assumptions, coordinates overlapping specifications, and serves as the liaison to the enforcement and reviewing officials and to the owner. The term is defined in the International Building Code and in the ICC Performance Code for Buildings and Facilities (where it is the Principal Design Professional).

understanding and skills to conduct the review, inspection, and approval tasks for which they are responsible. The outcome would further the integration of the disciplines in effective fire-safe design of buildings.

Relevance to WTC 7: Discerning the fire-structure interactions that led to the collapse of WTC 7 required research professionals with expertise in both disciplines. Assuring the safety of future buildings will require that participants in the design and review processes possess a combined knowledge of fire science, materials science, heat transfer, and structural engineering and design.

<u>Recommendation M (NIST NCSTAR 1 Recommendation 30).</u> NIST recommends that academic, professional short-course, and web-based training materials in the use of computational fire dynamics and thermostructural analysis tools be developed and delivered to strengthen the base of available technical capabilities and human resources.

Relevance to WTC 7: NIST stretched the state-of-the-art in the computational tools needed to reconstruct a fire-induced building collapse. This enabled identification of the critical processes that led to that collapse. Making these expanded tools and derivative, validated, and simplified modeling approaches usable by practitioners could prevent future disasters.

Appendix A
NATIONAL CONSTRUCTION SAFETY TEAM ACT

Public Law 107–231
107th Congress

An Act

To provide for the establishment of investigative teams to assess building performance and emergency response and evacuation procedures in the wake of any building failure that has resulted in substantial loss of life or that posed significant potential of substantial loss of life.

Oct. 1, 2002
[H.R. 4687]

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

National Construction Safety Team Act. 15 USC 7301 note.

SECTION 1. SHORT TITLE.

This Act may be cited as the "National Construction Safety Team Act".

SEC. 2. NATIONAL CONSTRUCTION SAFETY TEAMS. 15 USC 7301.

(a) ESTABLISHMENT.—The Director of the National Institute of Standards and Technology (in this Act referred to as the "Director") is authorized to establish National Construction Safety Teams (in this Act referred to as a "Team") for deployment after events causing the failure of a building or buildings that has resulted in substantial loss of life or that posed significant potential for substantial loss of life. To the maximum extent practicable, the Director shall establish and deploy a Team within 48 hours after such an event. The Director shall promptly publish in the Federal Register notice of the establishment of each Team. Federal Register, publication.

(b) PURPOSE OF INVESTIGATION; DUTIES.—

(1) PURPOSE.—The purpose of investigations by Teams is to improve the safety and structural integrity of buildings in the United States.

(2) DUTIES.—A Team shall—

(A) establish the likely technical cause or causes of the building failure;

(B) evaluate the technical aspects of evacuation and emergency response procedures;

(C) recommend, as necessary, specific improvements to building standards, codes, and practices based on the findings made pursuant to subparagraphs (A) and (B); and

(D) recommend any research and other appropriate actions needed to improve the structural safety of buildings, and improve evacuation and emergency response procedures, based on the findings of the investigation.

(c) PROCEDURES.—

(1) DEVELOPMENT.—Not later than 3 months after the date of the enactment of this Act, the Director, in consultation with the United States Fire Administration and other appropriate Federal agencies, shall develop procedures for the establishment and deployment of Teams. The Director shall Deadline.

(2) during reasonable hours, inspect any record (including any design, construction, or maintenance record), process, or facility related to the investigation;

(3) inspect and test any building components, materials, and artifacts related to the building failure; and

(4) move such records, components, materials, and artifacts as provided by the procedures developed under section 2(c)(1).

(b) AVOIDING UNNECESSARY INTERFERENCE AND PRESERVING EVIDENCE.—An inspection, test, or other action taken by a Team under this section shall be conducted in a way that—

(1) does not interfere unnecessarily with services provided by the owner or operator of the building components, materials, or artifacts, property, records, process, or facility; and

(2) to the maximum extent feasible, preserves evidence related to the building failure, consistent with the ongoing needs of the investigation.

(c) COORDINATION.—

(1) WITH SEARCH AND RESCUE EFFORTS.—A Team shall not impede, and shall coordinate its investigation with, any search and rescue efforts being undertaken at the site of the building failure.

(2) WITH OTHER RESEARCH.—A Team shall coordinate its investigation, to the extent practicable, with qualified researchers who are conducting engineering or scientific (including social science) research relating to the building failure.

(3) MEMORANDA OF UNDERSTANDING.—The National Institute of Standards and Technology shall enter into a memorandum of understanding with each Federal agency that may conduct or sponsor a related investigation, providing for coordination of investigations.

(4) WITH STATE AND LOCAL AUTHORITIES.—A Team shall cooperate with State and local authorities carrying out any activities related to a Team's investigation.

(d) INTERAGENCY PRIORITIES.—

(1) IN GENERAL.—Except as provided in paragraph (2) or (3), a Team investigation shall have priority over any other investigation of any other Federal agency.

(2) NATIONAL TRANSPORTATION SAFETY BOARD.—If the National Transportation Safety Board is conducting an investigation related to an investigation of a Team, the National Transportation Safety Board investigation shall have priority over the Team investigation. Such priority shall not otherwise affect the authority of the Team to continue its investigation under this Act.

(3) CRIMINAL ACTS.—If the Attorney General, in consultation with the Director, determines, and notifies the Director, that circumstances reasonably indicate that the building failure being investigated by a Team may have been caused by a criminal act, the Team shall relinquish investigative priority to the appropriate law enforcement agency. The relinquishment of investigative priority by the Team shall not otherwise affect the authority of the Team to continue its investigation under this Act.

(4) PRESERVATION OF EVIDENCE.—If a Federal law enforcement agency suspects and notifies the Director that a building failure being investigated by a Team under this Act may have

been caused by a criminal act, the Team, in consultation with the Federal law enforcement agency, shall take necessary actions to ensure that evidence of the criminal act is preserved.

15 USC 7304.

SEC. 5. BRIEFINGS, HEARINGS, WITNESSES, AND SUBPOENAS.

(a) GENERAL AUTHORITY.—The Director or his designee, on behalf of a Team, may conduct hearings, administer oaths, and require, by subpoena (pursuant to subsection (e)) and otherwise, necessary witnesses and evidence as necessary to carry out this Act.

(b) BRIEFINGS.—The Director or his designee (who may be the leader or a member of a Team), on behalf of a Team, shall hold regular public briefings on the status of investigative proceedings and findings, including a final briefing after the report required by section 8 is issued.

(c) PUBLIC HEARINGS.—During the course of an investigation by a Team, the National Institute of Standards and Technology may, if the Director considers it to be in the public interest, hold a public hearing for the purposes of—

(1) gathering testimony from witnesses; and

(2) informing the public on the progress of the investigation.

(d) PRODUCTION OF WITNESSES.—A witness or evidence in an investigation under this Act may be summoned or required to be produced from any place in the United States. A witness summoned under this subsection is entitled to the same fee and mileage the witness would have been paid in a court of the United States.

(e) ISSUANCE OF SUBPOENAS.—A subpoena shall be issued only under the signature of the Director but may be served by any person designated by the Director.

(f) FAILURE TO OBEY SUBPOENA.—If a person disobeys a subpoena issued by the Director under this Act, the Attorney General, acting on behalf of the Director, may bring a civil action in a district court of the United States to enforce the subpoena. An action under this subsection may be brought in the judicial district in which the person against whom the action is brought resides, is found, or does business. The court may punish a failure to obey an order of the court to comply with the subpoena as a contempt of court.

15 USC 7305.

SEC. 6. ADDITIONAL POWERS.

In order to support Teams in carrying out this Act, the Director may—

(1) procure the temporary or intermittent services of experts or consultants under section 3109 of title 5, United States Code;

(2) request the use, when appropriate, of available services, equipment, personnel, and facilities of a department, agency, or instrumentality of the United States Government on a reimbursable or other basis;

(3) confer with employees and request the use of services, records, and facilities of State and local governmental authorities;

(4) accept voluntary and uncompensated services;

(5) accept and use gifts of money and other property, to the extent provided in advance in appropriations Acts;

(6) make contracts with nonprofit entities to carry out studies related to purpose, functions, and authorities of the Teams; and

(7) provide nongovernmental members of the Team reasonable compensation for time spent carrying out activities under this Act.

SEC. 7. DISCLOSURE OF INFORMATION. 15 USC 7306.

(a) GENERAL RULE.—Except as otherwise provided in this section, a copy of a record, information, or investigation submitted or received by a Team shall be made available to the public on request and at reasonable cost. Records.

(b) EXCEPTIONS.—Subsection (a) does not require the release of—

(1) information described by section 552(b) of title 5, United States Code, or protected from disclosure by any other law of the United States; or

(2) information described in subsection (a) by the National Institute of Standards and Technology or by a Team until the report required by section 8 is issued.

(c) PROTECTION OF VOLUNTARY SUBMISSION OF INFORMATION.—Notwithstanding any other provision of law, a Team, the National Institute of Standards and Technology, and any agency receiving information from a Team or the National Institute of Standards and Technology, shall not disclose voluntarily provided safety-related information if that information is not directly related to the building failure being investigated and the Director finds that the disclosure of the information would inhibit the voluntary provision of that type of information.

(d) PUBLIC SAFETY INFORMATION.—A Team and the National Institute of Standards and Technology shall not publicly release any information it receives in the course of an investigation under this Act if the Director finds that the disclosure of that information might jeopardize public safety.

SEC. 8. NATIONAL CONSTRUCTION SAFETY TEAM REPORT. 15 USC 7307.

Not later than 90 days after completing an investigation, a Team shall issue a public report which includes— Deadline.

(1) an analysis of the likely technical cause or causes of the building failure investigated;

(2) any technical recommendations for changes to or the establishment of evacuation and emergency response procedures;

(3) any recommended specific improvements to building standards, codes, and practices; and

(4) recommendations for research and other appropriate actions needed to help prevent future building failures.

SEC. 9. NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY ACTIONS. 15 USC 7308.

After the issuance of a public report under section 8, the National Institute of Standards and Technology shall comprehensively review the report and, working with the United States Fire Administration and other appropriate Federal and non-Federal agencies and organizations—

(1) conduct, or enable or encourage the conducting of, appropriate research recommended by the Team; and

(2) promote (consistent with existing procedures for the establishment of building standards, codes, and practices) the

appropriate adoption by the Federal Government, and encourage the appropriate adoption by other agencies and organizations, of the recommendations of the Team with respect to—

(A) technical aspects of evacuation and emergency response procedures;

(B) specific improvements to building standards, codes, and practices; and

(C) other actions needed to help prevent future building failures.

15 USC 7309.

SEC. 10. NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY ANNUAL REPORT.

Deadline.

Not later than February 15 of each year, the Director shall transmit to the Committee on Science of the House of Representatives and to the Committee on Commerce, Science, and Transportation of the Senate a report that includes—

(1) a summary of the investigations conducted by Teams during the prior fiscal year;

(2) a summary of recommendations made by the Teams in reports issued under section 8 during the prior fiscal year and a description of the extent to which those recommendations have been implemented; and

(3) a description of the actions taken to improve building safety and structural integrity by the National Institute of Standards and Technology during the prior fiscal year in response to reports issued under section 8.

15 USC 7310.

SEC. 11. ADVISORY COMMITTEE.

(a) ESTABLISHMENT AND FUNCTIONS.—The Director, in consultation with the United States Fire Administration and other appropriate Federal agencies, shall establish an advisory committee to advise the Director on carrying out this Act and to review the procedures developed under section 2(c)(1) and the reports issued under section 8.

Deadline.

(b) ANNUAL REPORT.—On January 1 of each year, the advisory committee shall transmit to the Committee on Science of the House of Representatives and to the Committee on Commerce, Science, and Transportation of the Senate a report that includes—

(1) an evaluation of Team activities, along with recommendations to improve the operation and effectiveness of Teams; and

(2) an assessment of the implementation of the recommendations of Teams and of the advisory committee.

(c) DURATION OF ADVISORY COMMITTEE.—Section 14 of the Federal Advisory Committee Act shall not apply to the advisory committee established under this section.

15 USC 7311.

SEC. 12. ADDITIONAL APPLICABILITY.

The authorities and restrictions applicable under this Act to the Director and to Teams shall apply to the activities of the National Institute of Standards and Technology in response to the attacks of September 11, 2001.

SEC. 13. AMENDMENT.

Section 7 of the National Bureau of Standards Authorization Act for Fiscal Year 1986 (15 U.S.C. 281a) is amended by inserting ", or from an investigation under the National Construction Safety Team Act," after "from such investigation".

SEC. 14. CONSTRUCTION. 15 USC 7312.

Nothing in this Act shall be construed to confer any authority on the National Institute of Standards and Technology to require the adoption of building standards, codes, or practices.

SEC. 15. AUTHORIZATION OF APPROPRIATIONS. 15 USC 7313.

The National Institute of Standards and Technology is authorized to use funds otherwise authorized by law to carry out this Act.

Approved October 1, 2002.

LEGISLATIVE HISTORY—H.R. 4687:

HOUSE REPORTS: No. 107–530 (Comm. on Science).
CONGRESSIONAL RECORD, Vol. 148 (2002):
July 12, considered and passed House.
Sept. 9, considered and passed Senate, amended.
Sept. 17, House concurred in Senate amendment.

Appendix B
WORLD TRADE CENTER INVESTIGATION PUBLICATIONS

This report, NIST NCSTAR 1A, covers WTC 7, with a separate report on the two WTC towers. Supporting documentation of the techniques and technologies used in the investigation are in a set of companion reports that provide more details of the Investigation findings and the means by which these technical results were achieved. The titles of the full set of Investigation publications are:

NIST (National Institute of Standards and Technology). 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Final Report on the Collapse of the World Trade Center Towers.* NIST NCSTAR 1. Gaithersburg, MD, September.

NIST (National Institute of Standards and Technology). 2008. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Final Report on the Collapse of World Trade Center Building 7.* NIST NCSTAR 1A. Gaithersburg, MD.

Lew, H. S., R. W. Bukowski, and N. J. Carino. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Design, Construction, and Maintenance of Structural and Life Safety Systems.* NIST NCSTAR 1-1. National Institute of Standards and Technology. Gaithersburg, MD, September.

> Fanella, D. A., A. T. Derecho, and S. K. Ghosh. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Design and Construction of Structural Systems.* NIST NCSTAR 1-1A. National Institute of Standards and Technology. Gaithersburg, MD, September.
>
> Ghosh, S. K., and X. Liang. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Comparison of Building Code Structural Requirements.* NIST NCSTAR 1-1B. National Institute of Standards and Technology. Gaithersburg, MD, September.
>
> Fanella, D. A., A. T. Derecho, and S. K. Ghosh. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Maintenance and Modifications to Structural Systems.* NIST NCSTAR 1-1C. National Institute of Standards and Technology. Gaithersburg, MD, September.
>
> Grill, R. A., and D. A. Johnson. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Fire Protection and Life Safety Provisions Applied to the Design and Construction of World Trade Center 1, 2, and 7 and Post-Construction Provisions Applied after Occupancy*. NIST NCSTAR 1-1D. National Institute of Standards and Technology. Gaithersburg, MD, September.
>
> Razza, J. C., and R. A. Grill. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Comparison of Codes, Standards, and Practices in Use at the Time of the Design and Construction of World Trade Center 1, 2, and 7.* NIST NCSTAR 1-1E. National Institute of Standards and Technology. Gaithersburg, MD, September.

Grill, R. A., D. A. Johnson, and D. A. Fanella. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Comparison of the 1968 and Current (2003) New York City Building Code Provisions*. NIST NCSTAR 1-1F. National Institute of Standards and Technology. Gaithersburg, MD, September.

Grill, R. A., and D. A. Johnson. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Amendments to the Fire Protection and Life Safety Provisions of the New York City Building Code by Local Laws Adopted While World Trade Center 1, 2, and 7 Were in Use*. NIST NCSTAR 1-1G. National Institute of Standards and Technology. Gaithersburg, MD, September.

Grill, R. A., and D. A. Johnson. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Post-Construction Modifications to Fire Protection and Life Safety Systems of World Trade Center 1 and 2*. NIST NCSTAR 1-1H. National Institute of Standards and Technology. Gaithersburg, MD, September.

Grill, R. A., D. A. Johnson, and D. A. Fanella. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Post-Construction Modifications to Fire Protection, Life Safety, and Structural Systems of World Trade Center 7*. NIST NCSTAR 1-1I. National Institute of Standards and Technology. Gaithersburg, MD, September.

Grill, R. A., and D. A. Johnson. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Design, Installation, and Operation of Fuel System for Emergency Power in World Trade Center 7*. NIST NCSTAR 1-1J. National Institute of Standards and Technology. Gaithersburg, MD, September.

Sadek, F. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Baseline Structural Performance and Aircraft Impact Damage Analysis of the World Trade Center Towers.* NIST NCSTAR 1-2. National Institute of Standards and Technology. Gaithersburg, MD, September.

Faschan, W. J., and R. B. Garlock. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Reference Structural Models and Baseline Performance Analysis of the World Trade Center Towers.* NIST NCSTAR 1-2A. National Institute of Standards and Technology. Gaithersburg, MD, September.

Kirkpatrick, S. W., R. T. Bocchieri, F. Sadek, R. A. MacNeill, S. Holmes, B. D. Peterson, R. W. Cilke, C. Navarro. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Analysis of Aircraft Impacts into the World Trade Center Towers,* NIST NCSTAR 1-2B. National Institute of Standards and Technology. Gaithersburg, MD, September.

Gayle, F. W., R. J. Fields, W. E. Luecke, S. W. Banovic, T. Foecke, C. N. McCowan, T. A. Siewert, and J. D. McColskey. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Mechanical and Metallurgical Analysis of Structural Steel.* NIST NCSTAR 1-3. National Institute of Standards and Technology. Gaithersburg, MD, September.

Luecke, W. E., T. A. Siewert, and F. W. Gayle. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Contemporaneous Structural Steel Specifications.* NIST Special Publication 1-3A. National Institute of Standards and Technology. Gaithersburg, MD, September.

Banovic, S. W. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Steel Inventory and Identification.* NIST NCSTAR 1-3B. National Institute of Standards and Technology. Gaithersburg, MD, September.

Banovic, S. W., and T. Foecke. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Damage and Failure Modes of Structural Steel Components.* NIST NCSTAR 1-3C. National Institute of Standards and Technology. Gaithersburg, MD, September.

Luecke, W. E., J. D. McColskey, C. N. McCowan, S. W. Banovic, R. J. Fields, T. Foecke, T. A. Siewert, and F. W. Gayle. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Mechanical Properties of Structural Steels.* NIST NCSTAR 1-3D. National Institute of Standards and Technology. Gaithersburg, MD, September.

Banovic, S. W., C. N. McCowan, and W. E. Luecke. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Physical Properties of Structural Steels.* NIST NCSTAR 1-3E. National Institute of Standards and Technology. Gaithersburg, MD, September.

Evans, D. D., R. D. Peacock, E. D. Kuligowski, W. S. Dols, and W. L. Grosshandler. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Active Fire Protection Systems.* NIST NCSTAR 1-4. National Institute of Standards and Technology. Gaithersburg, MD, September.

Kuligowski, E. D., D. D. Evans, and R. D. Peacock. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Post-Construction Fires Prior to September 11, 2001.* NIST NCSTAR 1-4A. National Institute of Standards and Technology. Gaithersburg, MD, September.

Hopkins, M., J. Schoenrock, and E. Budnick. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Fire Suppression Systems.* NIST NCSTAR 1-4B. National Institute of Standards and Technology. Gaithersburg, MD, September.

Keough, R. J., and R. A. Grill. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Fire Alarm Systems.* NIST NCSTAR 1-4C. National Institute of Standards and Technology. Gaithersburg, MD, September.

Ferreira, M. J., and S. M. Strege. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Smoke Management Systems.* NIST NCSTAR 1-4D. National Institute of Standards and Technology. Gaithersburg, MD, September.

Gann, R. G., A. Hamins, K. B. McGrattan, G. W. Mulholland, H. E. Nelson, T. J. Ohlemiller, W. M. Pitts, and K. R. Prasad. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Reconstruction of the Fires in the World Trade Center Towers.* NIST NCSTAR 1-5. National Institute of Standards and Technology. Gaithersburg, MD, September.

Pitts, W. M., K. M. Butler, and V. Junker. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Visual Evidence, Damage Estimates, and Timeline Analysis.* NIST NCSTAR 1-5A. National Institute of Standards and Technology. Gaithersburg, MD, September.

Hamins, A., A. Maranghides, K. B. McGrattan, E. Johnsson, T. J. Ohlemiller, M. Donnelly, J. Yang, G. Mulholland, K. R. Prasad, S. Kukuck, R. Anleitner and T. McAllister. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Experiments and Modeling of Structural Steel Elements Exposed to Fire.* NIST NCSTAR 1-5B. National Institute of Standards and Technology. Gaithersburg, MD, September.

Ohlemiller, T. J., G. W. Mulholland, A. Maranghides, J. J. Filliben, and R. G. Gann. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Fire Tests of Single Office Workstations.* NIST NCSTAR 1-5C. National Institute of Standards and Technology. Gaithersburg, MD, September.

Gann, R. G., M. A. Riley, J. M. Repp, A. S. Whittaker, A. M. Reinhorn, and P. A. Hough. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Reaction of Ceiling Tile Systems to Shocks.* NIST NCSTAR 1-5D. National Institute of Standards and Technology. Gaithersburg, MD, September.

Hamins, A., A. Maranghides, K. B. McGrattan, T. J. Ohlemiller, and R. Anleitner. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Experiments and Modeling of Multiple Workstations Burning in a Compartment.* NIST NCSTAR 1-5E. National Institute of Standards and Technology. Gaithersburg, MD, September.

McGrattan, K. B., C. Bouldin, and G. Forney. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Computer Simulation of the Fires in the World Trade Center Towers.* NIST NCSTAR 1-5F. National Institute of Standards and Technology. Gaithersburg, MD, September.

Prasad, K. R., and H. R. Baum. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Fire Structure Interface and Thermal Response of the World Trade Center Towers.* NIST NCSTAR 1-5G. National Institute of Standards and Technology. Gaithersburg, MD, September.

Gross, J. L., and T. McAllister. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Structural Fire Response and Probable Collapse Sequence of the World Trade Center Towers.* NIST NCSTAR 1-6. National Institute of Standards and Technology. Gaithersburg, MD, September.

Carino, N. J., M. A. Starnes, J. L. Gross, J. C. Yang, S. Kukuck, K. R. Prasad, and R. W. Bukowski. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Passive Fire Protection.* NIST NCSTAR 1-6A. National Institute of Standards and Technology. Gaithersburg, MD, September.

Gross, J., F. Hervey, M. Izydorek, J. Mammoser, and J. Treadway. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Fire Resistance Tests of Floor Truss Systems.* NIST NCSTAR 1-6B. National Institute of Standards and Technology. Gaithersburg, MD, September.

Zarghamee, M. S., S. Bolourchi, D. W. Eggers, Ö. O. Erbay, F. W. Kan, Y. Kitane, A. A. Liepins, M. Mudlock, W. I. Naguib, R. P. Ojdrovic, A. T. Sarawit, P. R Barrett, J. L. Gross, and T. P. McAllister. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Component, Connection, and Subsystem Structural Analysis.* NIST NCSTAR 1-6C. National Institute of Standards and Technology. Gaithersburg, MD, September.

Zarghamee, M. S., Y. Kitane, Ö. O. Erbay, T. P. McAllister, and J. L. Gross. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Global Structural Analysis of the Response of the World Trade Center Towers to Impact Damage and Fire.* NIST NCSTAR 1-6D. National Institute of Standards and Technology. Gaithersburg, MD, September.

Averill, J. D., D. S. Mileti, R. D. Peacock, E. D. Kuligowski, N. Groner, G. Proulx, P. A. Reneke, and H. E. Nelson. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Occupant Behavior, Egress, and Emergency Communication.* NIST NCSTAR 1-7. National Institute of Standards and Technology. Gaithersburg, MD, September.

Fahy, R., and G. Proulx. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Analysis of Published Accounts of the World Trade Center Evacuation.* NIST NCSTAR 1-7A. National Institute of Standards and Technology. Gaithersburg, MD, September.

Zmud, J. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Technical Documentation for Survey Administration.* NIST NCSTAR 1-7B. National Institute of Standards and Technology. Gaithersburg, MD, September.

Lawson, J. R., and R. L. Vettori. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: The Emergency Response Operations.* NIST NCSTAR 1-8. National Institute of Standards and Technology. Gaithersburg, MD, September.

McAllister, T. P., R. G. Gann, J. D. Averill, J. L. Gross, W. L. Grosshandler, J. R. Lawson, K. B. McGrattan, H. E. Nelson, W. M. Pitts, K. R. Prasad, F. H. Sadek. 2008. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Structural Fire Response and Probable Collapse Sequence of World Trade Center Building 7.* NIST NCSTAR 1-9. National Institute of Standards and Technology. Gaithersburg, MD.

MacNeill, R., S. Kirkpatrick, B. Peterson, and R. Bocchieri, 2008. Federal Build*ing and Fire Safety Investigation of the World Trade Center Disaster: Global Structural Analysis of the Response of World Trade Center Building 7 to Fires and Debris Impact Damage*. NIST NCSTAR 1-9A. National Institute of Standards and Technology, Gaithersburg, MD.